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## AN ANALYSIS OF A CYCLONE ON A SMALL SYNOPTIC SCALE[1]

JEROME SPAR

New York University, New York, N. Y.

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ABSTRACT

A fast-moving, rapidly-deepening cyclone is analyzed mainly by means of hourly airways sequence reports in the Atlantic coastal plain of the United States.

Six-hourly rainfall maps are presented showing the concentration of heavy rain along the cyclone path, and the strongly convective character of the cyclonic precipitation.

Gusty surface winds are found mainly in the warm sector during the early stages of the cyclone. The momentum of the surface gusts is derived from that of higher layers and comes down to the surface in bursts through the unstable warm air. Because the stability of the frontal zone prevents the downward transport of gust momentum, the surface winds in the cold air are much lighter than in the warm air. However, in places the front is penetrated by the gusts, and the resulting vertical mixing brings warm air to the surface causing an acceleration of the surface warm front. As the cyclone deepens, the gust velocities increase in the cold air in proportion to the increase of pressure gradient. The momentum of the low-level jet at the top of the friction layer penetrates to the surface most readily when the surface pressure gradient force does not oppose the direction of the jet.

An analysis of hourly pressure changes shows the existence of large-amplitude, high-speed pressure pulses moving across the cyclone. The pulses result in deformation of the pressure field, the generation of secondary centers, and erratic motion of the cyclone.

### 1. INTRODUCTION

The scale on which weather analysis is carried out determines to a large extent the nature of the phenomena that are found. Every scale has its own characteristic phenomena which other scales of analysis may not reveal. Indeed much controversy in meteorology has resulted from the comparison of analyses on different scales; for analysts, examining the same system but under different degrees of magnification, may see quite different structures and processes.

The surface synoptic scale (corresponding to the separation of surface weather stations), to which synoptic meteorologists have become accustomed during the past 100 years, reached its zenith of productivity in the work of the Norwegian school about 1920. Since that time, and especially in the last 15 years, meteorological analysis has been extended over a broad spectrum of scales, but with some tendency for a concentration of research effort on a large scale corresponding to the hemispheric radiosonde network, and on a small scale corresponding to radar studies of rainstorm morphology and various dense networks of raingages and microbarographs. (The microscales used in some micrometeorological and turbulence studies are, of course, still smaller.)

There is a rough correspondence of the time scale to the space scale of the analyses that is dictated by the cost of the observations and the velocities of disturbances.

Weather forecasters, particularly in aviation forecasting, are accustomed to working with the surface

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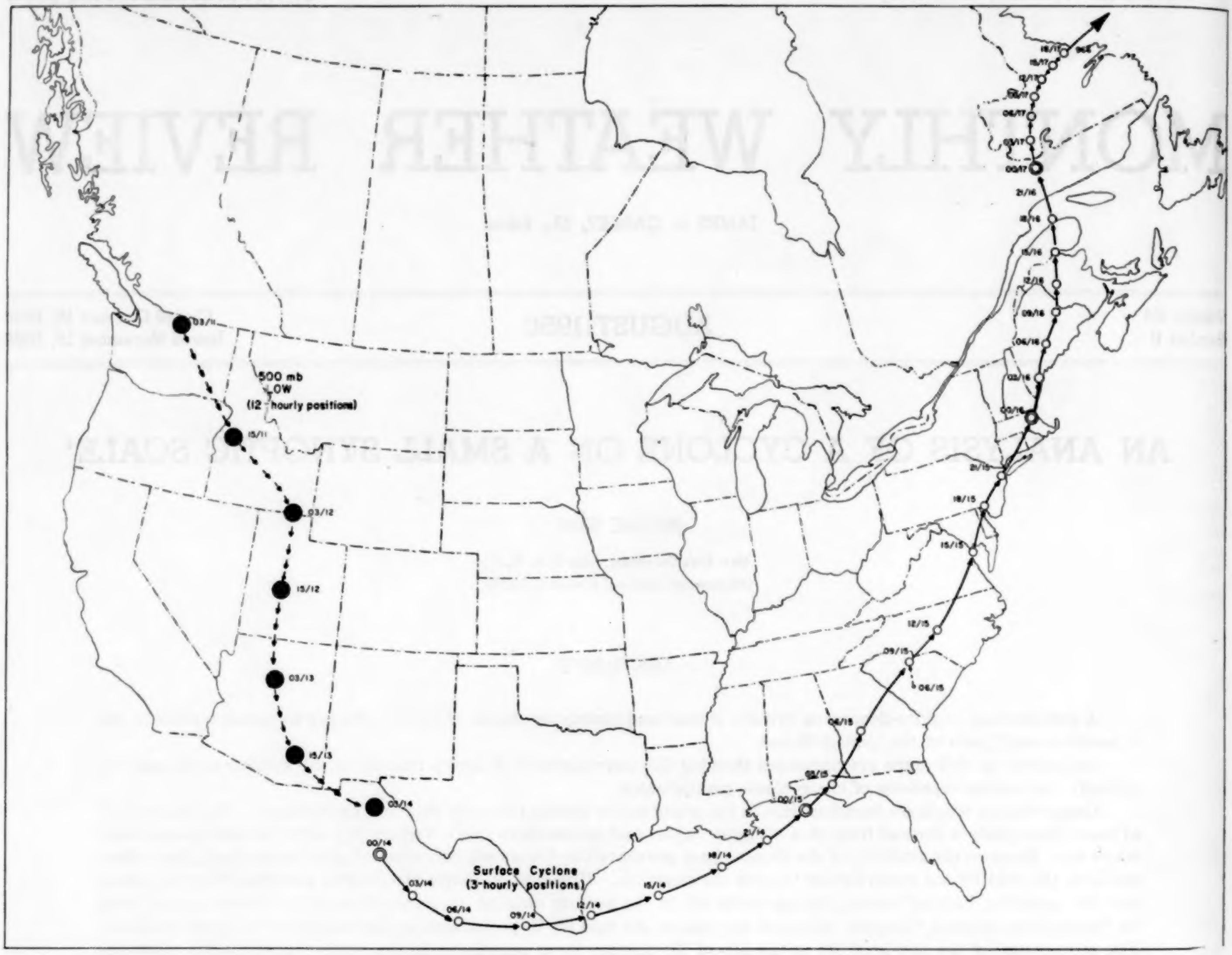


FIGURE 1.—Tracks of the 500-mb. Low (12-hourly positions) February 11–14, 1953, and the sea level cyclone (3-hourly positions) February 14–17, 1953.

synoptic, upper air, and radar scales. But a considerable part of the forecasters' attention is also devoted to what may be termed the "small synoptic scale" for which the characteristic distance in the United States is the separation between the hourly reporting airways weather stations and the characteristic time is one hour or less. When examined on this scale, the structure of fronts, the shape of the pressure field, and the distribution of rain and wind may bear little resemblance to models based on larger-scale analyses.

The case study described below was undertaken as an approach to the problem of devising a model of cyclone development in the eastern United States as seen on the small synoptic scale. However, it is not suggested that this one example is in any way a representative model of cyclogenesis. The cyclone selected was characterized by widespread heavy rain, rapid deepening, and very fast movement, all of which occurred over a region containing a suitably dense network of weather stations. It is not to be expected that other cyclones will have quite the same structure and behavior.

The original map scale used for most of the analysis was about 1:4,000,000. The airways sequence reporting stations, for which pressure and wind analyses were constructed every hour, form an irregular grid on the Atlantic seaboard with an average separation of about 50 miles (greater in the south and smaller in the north). Rainfall data, on the other hand, were obtained in 6-hourly increments for a network consisting of cooperative recording-gage stations as well as first order Weather Bureau stations.[2] The average distance between the raingage stations used was about 25 miles. This is considerably greater than is desirable for most hydrologic purposes and, with little effort, the distance could have been reduced by adding stations. However, this would have resulted in a non-uniform distribution of gage density, so that the scale

[2] Rainfall data were supplied by the National Weather Records Center, Asheville, N. C.

of the rainfall analysis would have been variable and would not correspond to that of the pressure and wind analyses.

Although some attention was given to the upper air data in this study, it is obvious that analysis on the small scale must be restricted largely to surface weather observations. Because of the relatively long time intervals and large distances between upper air reports, it is difficult, in general, to describe anything but the environment of a cyclone in three dimensions. Its internal structure is revealed only occasionally and incompletely by the synoptic upper air data.

## 2. THE STORM TRACK

The cyclone described below first appeared on the surface weather map in northern Mexico about 0030 GMT February 14, 1953, although it apparently originated much earlier at upper levels. The earlier phases in the life history of the storm and its behavior as it moved eastward into the Gulf of Mexico on the 14th have been described by Jones and Roe [1]. The paths of the 500-mb. Low and the surface cyclone are shown in figure 1.

A low center was found on the 500-mb. map for 0300 GMT February 11 over northern Washington prior to the appearance of the surface cyclone. In the next three days the 500-mb. Low moved southeastward (about 500 miles per day) to northern Mexico, where the surface cyclone appeared southeast of the upper Low. After the formation of the surface Low, the 500-mb. cell was absorbed in the southern end of the deepening trough. The 500-mb. Low never reappeared as a closed system but remained embedded in the southern end of the trough in the form of an area of weak pressure gradient and light wind. The surface cyclone moved eastward into the Gulf of Mexico, then turned northeastward and raced across the Atlantic coastal region on the 15th.

The cyclone center reentered the United States near Panama City, Fla. about 0330 GMT on the 15th after traversing the northwestern portion of the Gulf. Up to this time the average speed of the cyclone had been 46 knots, it had deepened about 2 mb. in 27 hours, and had been accompanied by heavy rain and very gusty winds along the Gulf coast from Louisiana to Florida.

After crossing the coast the cyclone continued its rapid progress northeastward across the coastal plain. At 0030 GMT on the 16th the center passed over Boston having travelled at an average speed of 43 knots in the preceding 24 hours. During this period the cyclone deepened 19 mb. Nine hours later the pressure reached a minimum value of 970 mb., a drop of 25 mb. in 24 hours. (In the 3 hours between 1530 and 1830 GMT on the 15th the central pressure fell 5 mb.) The deepening rate of the cyclone is shown in figure 2.

Moving now with a speed of about 25 knots the storm crossed the Gaspé Peninsula on the 16th, entered southern Quebec, and then recurved again across Labrador. As the cyclone left the Labrador coast on the 17th the central pressure again fell about 4 mb. But in the next three days

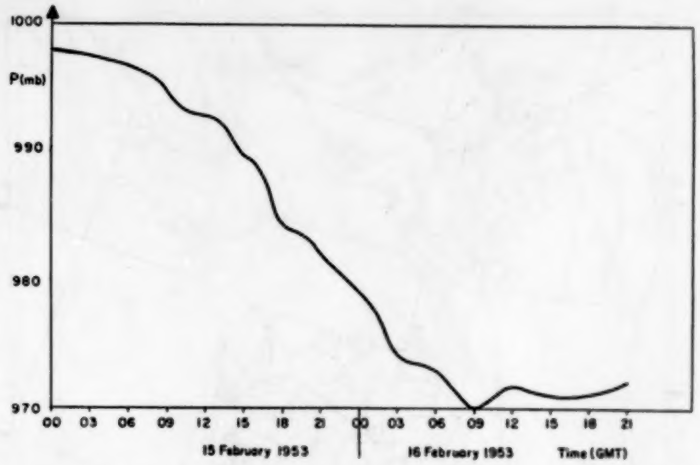


Figure 2.—Central pressure of the cyclone, February 15–16, 1953.

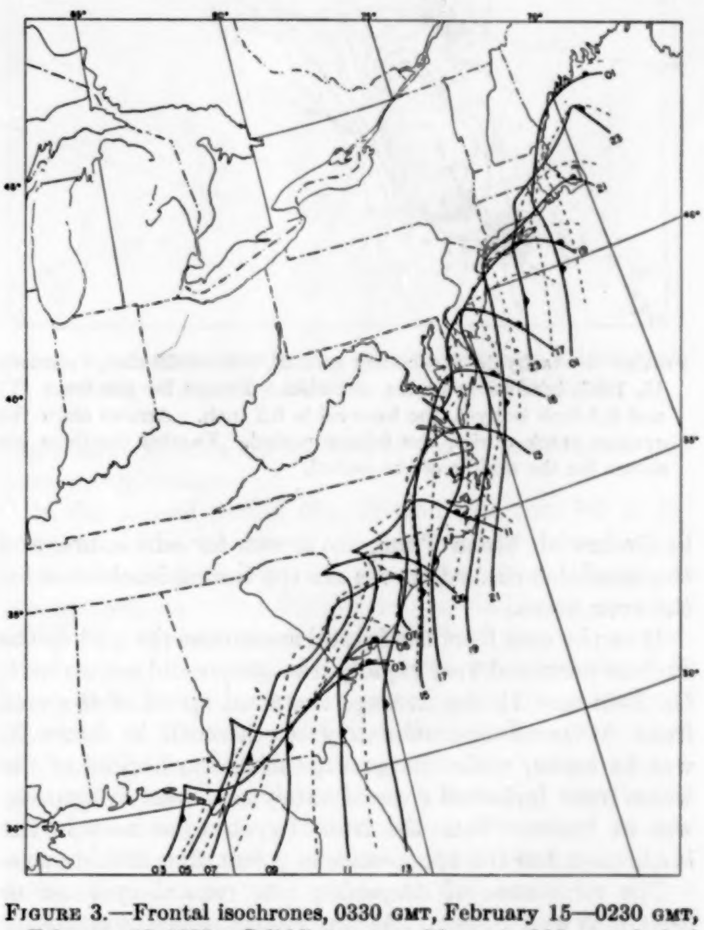

Figure 3.—Frontal isochrones, 0330 GMT, February 15—0230 GMT, February 16, 1953. Solid lines are positions at odd hours, dashed lines at even hours.

the cyclone slowly filled as it drifted eastward south of Greenland.

Hourly surface maps were drawn for the period 0330 GMT February 15, to 0230 GMT February 16, 1953, during which time the cyclone traversed the Atlantic seaboard from Florida to Maine. The hourly positions of the fronts (frontal isochrones) taken from the hourly surface maps are shown in figure 3. The solid curves, which are labeled

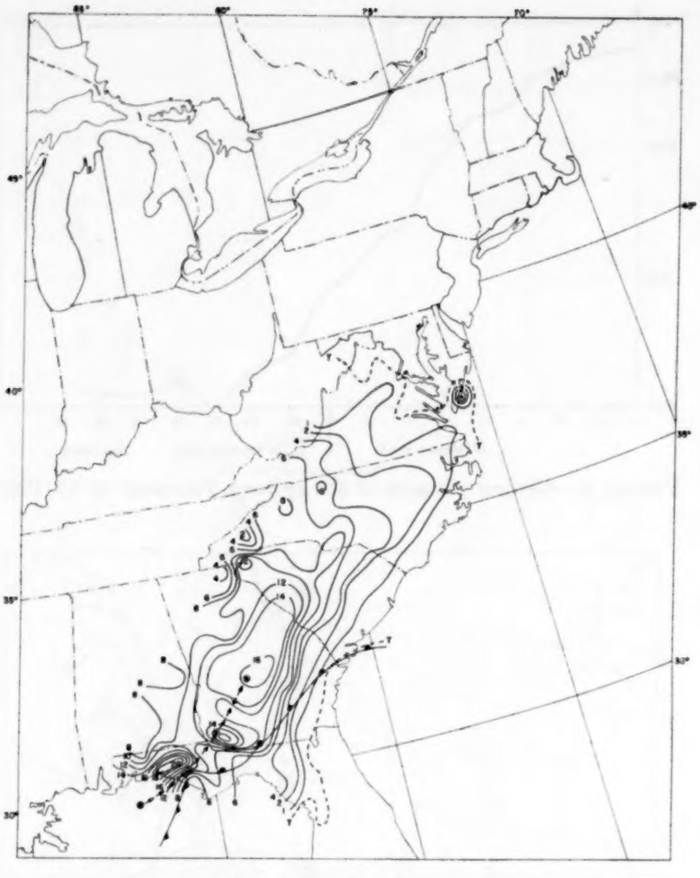

FIGURE 4.—Isohyets of 6-hourly rainfall, 0030–0630 GMT, February 15, 1953, labelled in tenths of inches. Except for the trace (T) and 0.1-inch isohyet, the interval is 0.2 inch. Arrows show the cyclone track during the 6-hour period. Frontal positions are shown for the middle of the period.

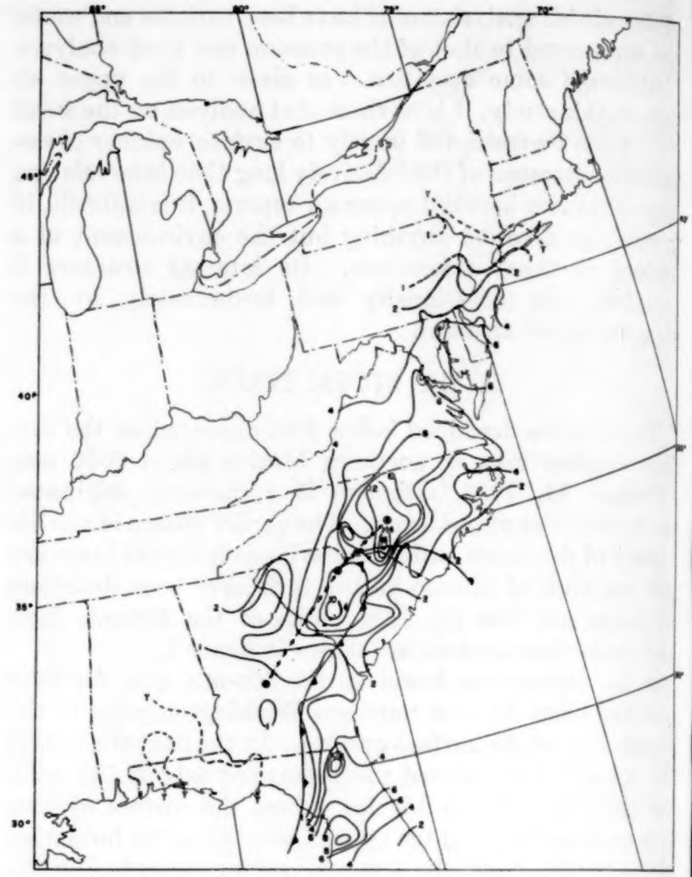

FIGURE 5.—Isohyets of 6-hourly rainfall, 0630–1230 GMT, February 15, 1953. (See legend for fig. 4.)

in Greenwich Mean Time, are drawn for odd hours, and the unlabeled dashed curves are the frontal isochrones for the even hours.

It can be seen from the frontal isochrones that, while the cyclone deepened very rapidly, the system did not occlude. On February 15 the average eastward speed of the cold front (oriented approximately north-south in figure 3) was 24 knots, while the average northward speed of the warm front (oriented approximately east-west in figure 3) was 31 knots. Thus the frontal system, as seen in the isochrones, has the appearance of a fast, flat, stable wave.

The reluctance of deepening east coastal cyclones to occlude is well known. At times the absence of occlusion may be ascribed to the fact that when the low center is on the coast the cold air west of the cold front may be advancing over land while the cold air north of the warm front is retreating over water. The smaller frictional drag at the sea surface thus permits the warm front to advance more rapidly than the cold front, and the warm sector remains open. However, in the present case it can be seen that the warm front advanced quite as rapidly over land (e. g., between 0930 and 1330 GMT) as it did over water. It will be seen below that the rapid movement of the warm front was caused by the downward transport of warm air through the frontal surface. The mixing of the potentially warmer air from above the front with the cool air below the front eradicates the "old" warm front and produces a "new" warm front well to the north. The "new" warm air south of the "new" warm front is, of course, not as warm as was the original warm sector air. This is due partly to the non-adiabatic cooling of the northward-moving warm air mass and partly to the mixing of cold air with the sinking warm mass. Since there is strong vertical wind shear through the front, the vertical mass exchange also brings strong southerly momentum to the surface ahead of the front, and this too contributes to the northward acceleration of the warm front.

## 3. RAINFALL

Six-hourly rainfall amounts were obtained from 275 recording raingages uniformly distributed throughout the eastern United States. Both cooperative and first order stations were used to give an average gage density of about one in 850 square miles.

The scale of the raingage network is about half as large as that of the airways network employed in the synoptic analysis. It is thus capable of revealing many

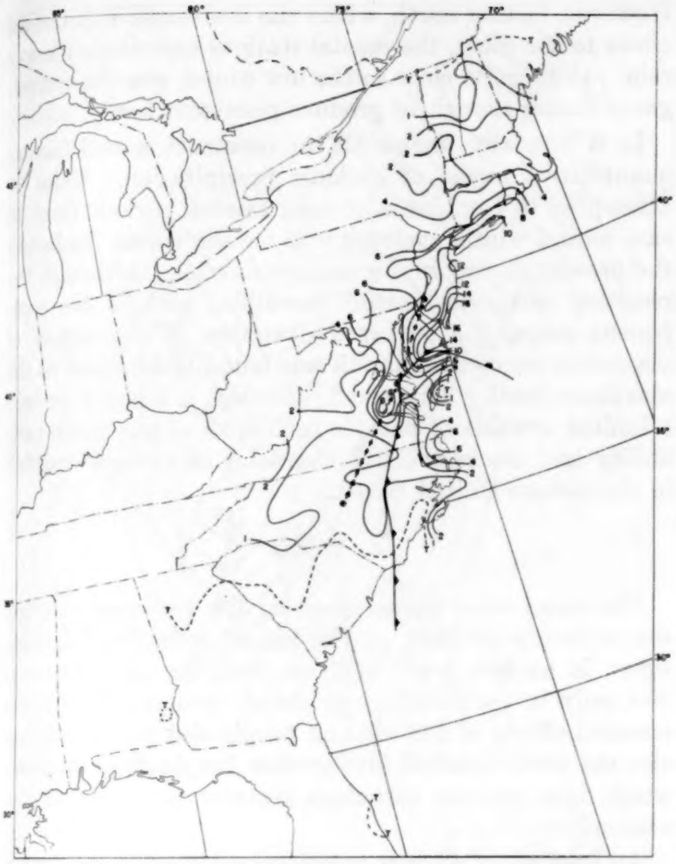

FIGURE 6.—Isohyets of 6-hourly rainfall, 1230–1830 GMT, February 15, 1953. (See legend for fig. 4.)

FIGURE 7.—Isohyets of 6-hourly rainfall, 1830 GMT, February 15–0030 GMT, February 16, 1953. (See legend for fig. 4.)

small convective rain cells which the synoptic analysis may not show. Because 6-hour totals are used and the life of a convective rain cell may be at least several hours, the effective scale of the raingage network is even smaller than the distance between gages would indicate.

The 6-hourly rainfall distributions associated with the cyclone are shown for the four periods of February 15, 1953 in figures 4–7. Isohyets are drawn for a trace (T), one tenth of an inch, two tenths, and at intervals of two tenths of an inch thereafter. Also shown on the isohyetal maps are the cyclone track during the 6-hour period and the frontal positions at the middle of the period.

The heaviest rain on February 15, both in regard to maximum point values and the area covered, occurred in the first period (fig. 4) when the cyclone was farthest south. During this period, when the cyclone was still deepening rather slowly, 6-hour rainfall amounts in excess of 2 inches fell in western Florida. The axis of maximum precipitation was oriented southwest-northeast, approximately along the cyclone track and parallel to the mid-tropospheric circulation. The rain fell mainly in the cold air north of the front, although light rain did fall also in the warm sector. It is clear from the isohyets that the rainfall had the character of cellular convection superimposed on a broad area of steady and rather uniform precipitation.

In the second period (fig. 5) moderate rain fell in the warm sector as a series of pre-frontal showers and squall lines moved eastward over the region from Florida to North Carolina. But the heaviest rainfall again occurred along the cyclone track and ahead of the low center. The center of gravity of the rainfall travelled about 50 knots toward the northeast, with about the velocity of the wind at 700 mb. Although the cellular character of the rainfall is still evident in figure 5, the strong convection which produced more than 2 inches of rain in the first period apparently diminished somewhat in the second. The maximum 6-hour rainfall observed in the latter period was 1.6 inches. It can easily be shown that the vertical velocity necessary to produce rainfall of this intensity must be at least one meter per second. Thus the characteristically heavy cyclonic precipitation in winter requires vertical motions considerably greater than the gentle upgliding associated with the large-scale circulation.

Between 1230 and 1830 GMT (fig. 6) pre-frontal showers produced patches of light precipitation in the warm air, while the heaviest rainfall (1.6 inches) again fell in the cold air ahead of the warm front.

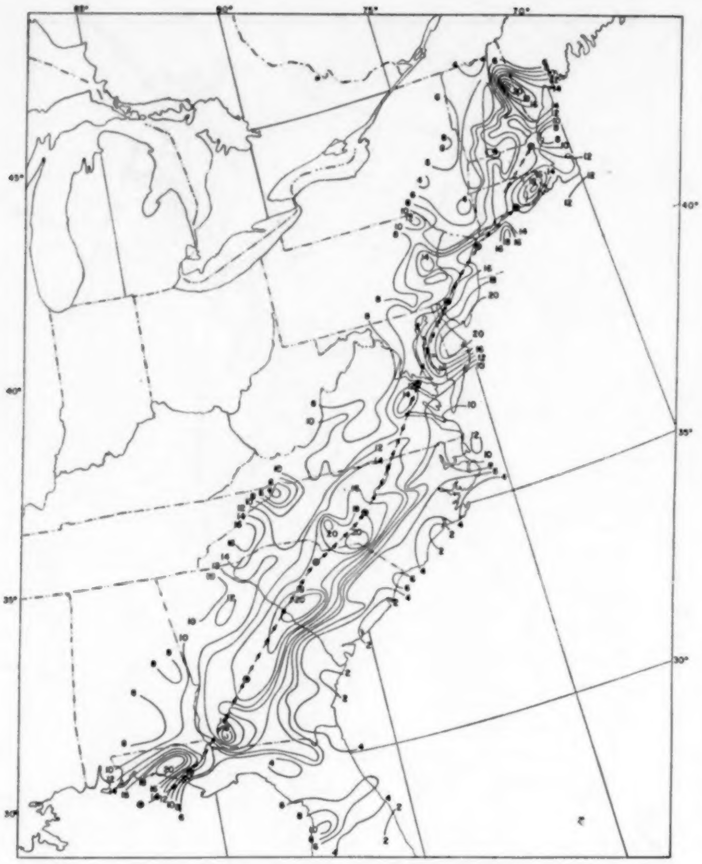

FIGURE 8.—Isohyets of 24-hourly rainfall and 24-hour cyclone track, 0030 GMT, February 15–0030 GMT, February 16, 1953.

In the last period shown (fig. 7) the precipitation was also concentrated north of the cyclone. (We have, of course, no information about the rainfall amounts over the ocean.) The heaviest rainfall (2.5 inches) was observed on Mt. Washington, N. H. That this was not entirely orographic is shown by the fact that 1.4 inches fell at Portland, Maine, at the same time. This rainfall maximum (another maximum of 1.4 inches is found over Providence, R. I.) appears to have been connected with the secondary cyclone center which appeared over Hartford at 2330 GMT and which is shown near Boston at 0030 GMT in figure 7.

The patterns of 6-hourly rainfall described above are in accord with the familiar cyclone model. With the exception of pre-frontal showers, the rain occurred mainly ahead of the cyclone center and the heaviest amounts fell approximately along the cyclone track. This is shown more clearly in figure 8 in which isohyets of the total 24-hour rainfall on February 15 are drawn, together with the 24-hour cyclone track. The cyclone track almost coincides with the axis of maximum rainfall. Exceptions are the orographic rainfall in New Hampshire and the western part of North Carolina, and the heavy rain in southern New Jersey which accompanied the passage of the cold front.

Very little rain fell along the coast south of Hatteras either in the warm sector or ahead of the warm front. However, farther north, where the low center approached closer to the coast, the coastal stations experienced heavy rain. Only quite close to the low center was the convergence strong enough to produce persistent heavy rain.

It is virtually impossible to construct a satisfactory quantitative model of cyclonic precipitation. Reiss [2] attempted to combine 43 6-hour rainfall periods from 10 east coastal winter cyclones with similar tracks (including the present storm) into a composite map. Although the resulting composite pattern resembled each of the component maps, the standard deviation in the region of maximum composite rainfall was found to be equal to the maximum itself. This result, although it is based on only a limited amount of data, is indicative of the great variability and the convective character of cyclonic rainfall in the eastern United States.

## 4. WIND

The mean wind (represented by the 1-minute average, the 5-minute average, or the fastest mile) is of less interest in surface wind analysis than the gust velocity. Not only is the latter more closely connected with the physical effects of the wind on people and structures, but also the gust velocities give greater insight than do mean winds into various turbulent transfer processes in the atmosphere.

An analysis of all gust velocities reported in the hourly and special airways observations on February 15, 1953, in the Atlantic coastal region led to the following conclusions regarding the low-level wind structure in the cyclone:

1. The relation between surface wind and sea level pressure distribution is different in the various sectors of the cyclone and in the different stages of the life history of the storm, and depends on the vertical shear and stability in the lower levels.

2. In the early stages of the cyclone the strongest gusts were found in the warm sector. In the cold air northeast of the low center the wind was generally light and markedly cross-isobaric.

3. The cold air under the warm frontal surface was shallow and stable with strong vertical shear through the frontal zone. The momentum of the fast-moving warm air above the front was generally shielded from the surface by the frontal stability. However, this momentum did occasionally penetrate to the surface producing isolated gusts ahead of the warm front. When this occurred, the vertical mixing caused an increase in the surface temperature ahead of the warm front and an increase in the surface wind component away from the warm front in the cold air, so that the front accelerated northward.

4. In the early stages of the storm the gustiness was not accompanied by corresponding increases in the sea level pressure gradient. However, as the storm deepened, the strong easterly winds which developed northeast of the low center were associated with roughly proportional increases in the sea level pressure gradient. This observa-

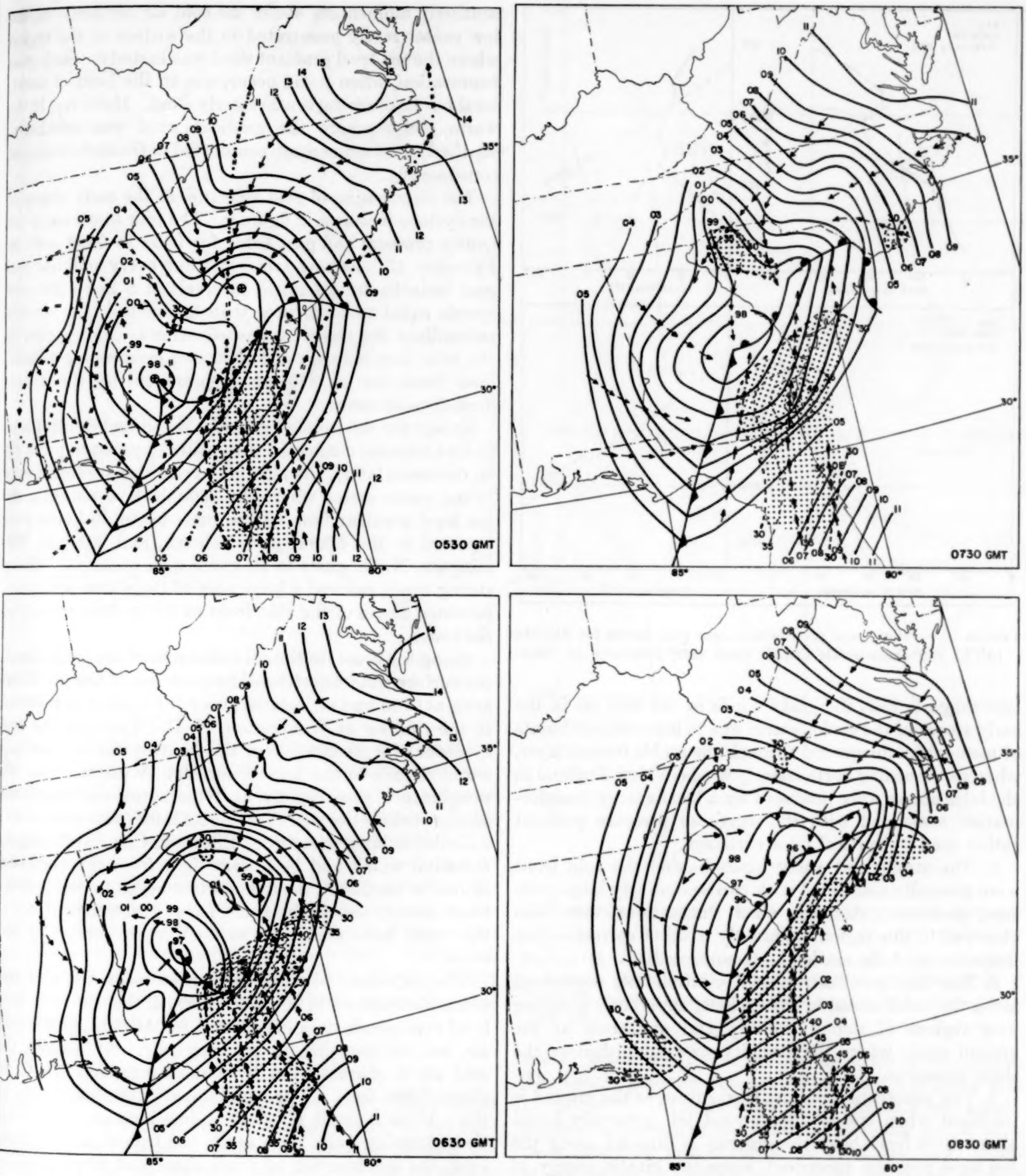


Figure 9.—Hourly surface maps, 0530–0830 GMT, February 15, 1953. Solid lines are 1-millibar isobars. Dashed lines are gust isotachs labeled in knots. The areas in which the gust velocities exceed 30 knots are stippled. Dashed arrows show the surface wind direction. The double dash-dot-dot arrows on the 0530 GMT map are 0300 GMT geostrophic streamlines (contours) at 850 mb.

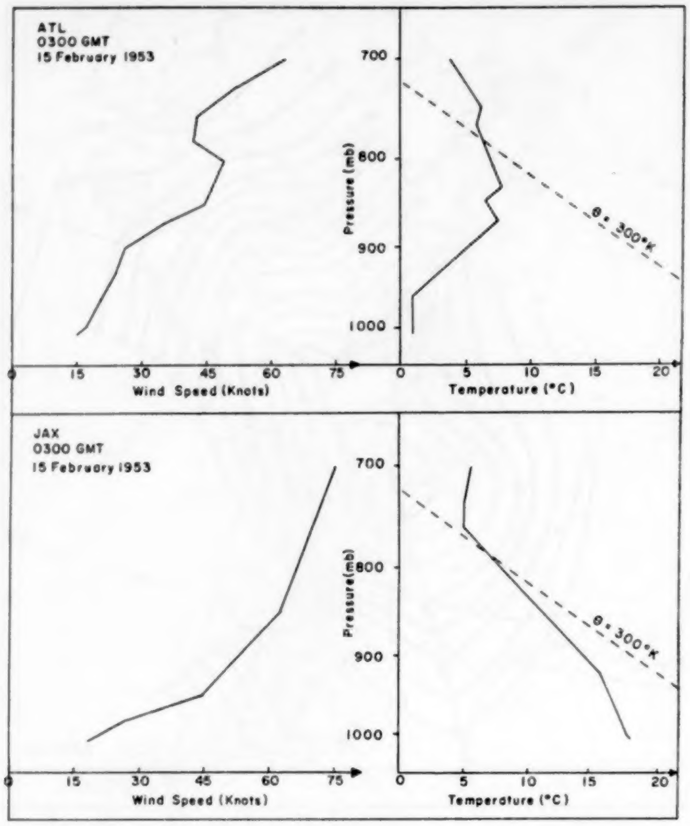


Figure 10.—Wind speed profiles and lapse rate curves for Atlanta (ATL) and Jacksonville (JAX), 0300 GMT, February 15, 1953.

tion suggests that the gusty winds in the cold air in the early stages of the cyclone were due to intermittent bursts of momentum downward through the stable frontal layer, whereas the strong northeasterly winds in New England in the later stages were produced by a local energy transformation associated with the increased pressure gradient rather than by vertical mass exchange.

5. The strong and gusty winds behind the cold front were generally associated with correspondingly large pressure gradients, although wind fluctuations were also observed in this region apparently without corresponding fluctuations of the sea level pressure gradient.

6. The "first gust" advanced discontinuously northward along the coast ahead of the cyclone, apparently skipping over regions of strong stability and appearing at the ground again where the stability was diminished or the shear excessive.

7. The penetration of gust momentum to the ground is inhibited when the low level wind jet (generally found about 5000 feet above the ground) is directed along the sea level pressure ascendent, since the kinetic energy of the gust is then consumed in work done against the pressure gradient force. A 40-knot gust has a kinetic energy of approximately 2 megergs gm$^{-1}$. It is easily shown that a particle with this kinetic energy moving along a horizontal pressure ascendent of 3 mb. per 100 km. will lose all its kinetic energy in a distance of about 60 km. The strong southerly momentum above the cold air northeast of the low center rarely penetrated to the surface in the region where the sea level gradient wind was easterly. Such gust penetration, when it did occur, was in the form of short, local bursts of strong southeasterly wind. However, in the warm sector where the gradient wind was southerly, southerly gust momentum penetrated to the surface almost continuously.

The distribution of gust velocities in the early stages of the cyclone is shown in figure 9. The four maps show the hourly pressure and gust fields for 0530 to 0830 GMT on February 15. Isobars are drawn for every millibar and gust isotachs are drawn at intervals of 5 knots for gust speeds equal to or greater than 30 knots. The surface streamlines are shown as dashed arrows. Also shown on the 0530 GMT map are the 0300 GMT geostrophic streamlines (contours) at 850 mb., represented by the double dash-dot-dot arrows.

Except for the isolated gusts in North and South Carolina which were connected with a strong pressure pulse (to be discussed later), the high gust velocities are found only in the warm sector where the 850-mb. flow parallels the sea level gradient flow. Here gusts up to 50 knots were reported in the 4-hour period shown, and later, at Wilmington, N. C., gusts to 70 knots were observed. These strong winds covered a large area of the warm sector and persisted ahead of the cold front as the cyclone moved up the coast.

Along the coast, in the cold air north of the warm front, the surface wind velocities did not exceed 15 knots. However, at 0730 GMT an isolated gust of 31 knots was reported in the cold air at Wilmington, N. C. This was the first evidence of a penetration of the front by the fast-moving warm air above the frontal surface. With the gust the temperature rose rapidly at Wilmington and the front accelerated northward. Two hours later (map not shown) a similar isolated gust struck Elizabeth City, N. C. Again the wind which had been very light from the northeast shifted to southeast, the temperature began to rise, and the front accelerated northward. These gust penetrations of the warm front continued as the cyclone moved up the coast.

The difference between the structure of the cold and warm air is shown in figure 10 in which the 0300 GMT low-level rawinsonde data are plotted for Atlanta, in the cold air, and Jacksonville, in the warm air. At Atlanta the cold air is characterized by a deep inversion (7° C. in about 5,000 feet). The wind shear in the lower part of the cold air is small, although it does increase with elevation becoming quite large across the frontal zone. However, the combination of small shear and large stability in the lower 3,000 feet over Atlanta precludes gust penetration to the surface. At Jacksonville on the other hand there is no cold shielding layer, and the wind shear, especially in the lower layers, is large so that the strong momentum above the surface can (and did) penetrate to the ground.

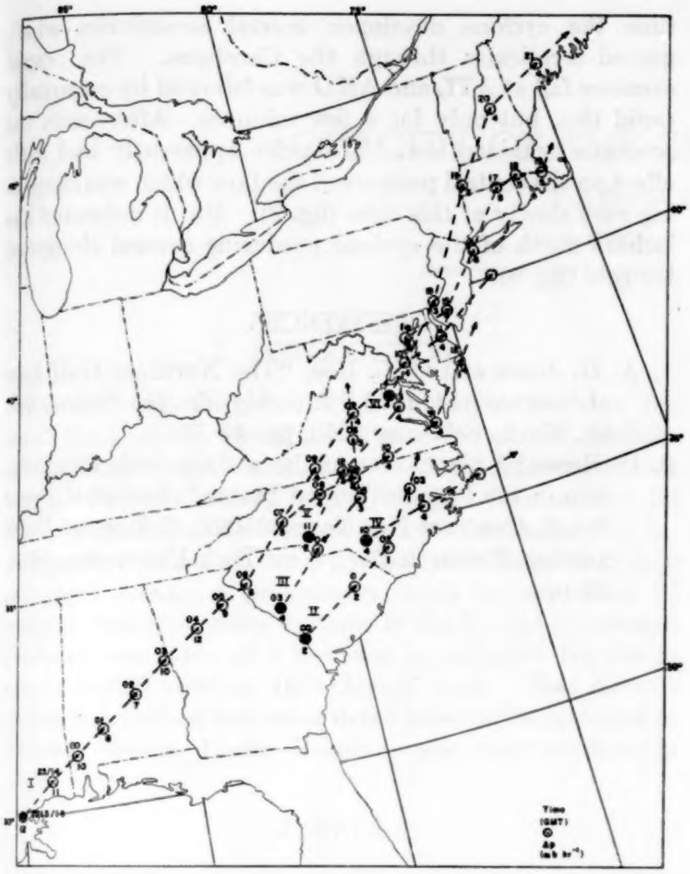

FIGURE 11.—Tracks of 1-hourly katallobaric centers, February 15, 1953. Solid circles show the initial positions of each of the six centers.

Beginning about 1730 GMT, easterly gusts in excess of 40 knots began to develop along the New England coast northeast of the cyclone. These gusts, which appeared to develop over the ocean, were associated largely with the development of a strong pressure gradient north of the warm front rather than with a vertical exchange of momentum. The absence of gusty winds north of the cyclone earlier in its history was apparently due to the relative weakness of the pressure gradient and the greater roughness of land compared with the ocean. In addition there was a noticeable decrease in the vertical stability northeast of the cyclone as it deepened which also contributed to the increased gustiness.

## 5. PRESSURE PULSES

Hourly isallobars drawn in conjunction with the analysis of the hourly surface maps revealed a series of pressure pulses moving rapidly across the cyclone toward the northeast. In the 24-hour period described previously six individual pulses were observed. The time, path, and 1-hourly pressure changes of each pulse are shown in figure 11. The pulses are identified with 1-hour katallobaric centers which could be followed from map to map for at least 3 hours. The average speed of the centers

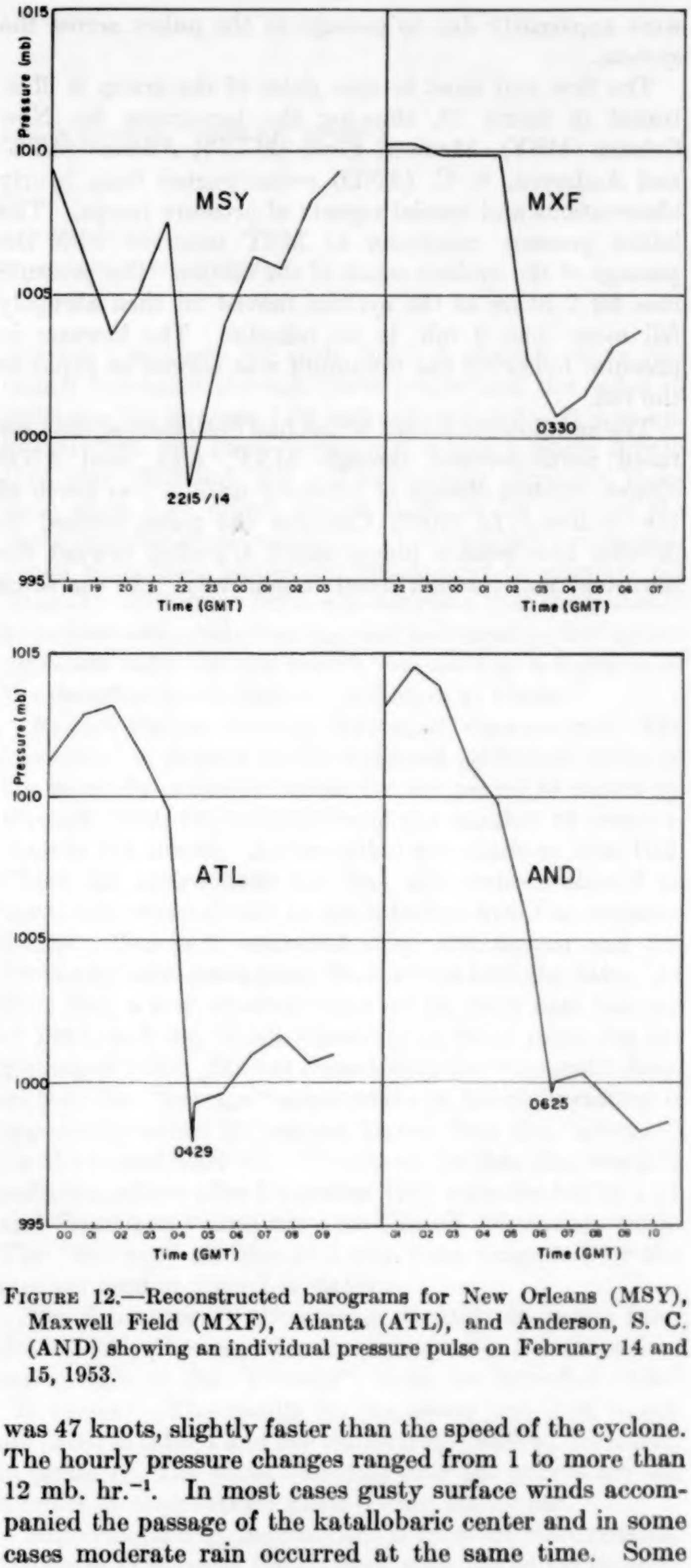


FIGURE 12.—Reconstructed barograms for New Orleans (MSY), Maxwell Field (MXF), Atlanta (ATL), and Anderson, S. C. (AND) showing an individual pressure pulse on February 14 and 15, 1953.

was 47 knots, slightly faster than the speed of the cyclone. The hourly pressure changes ranged from 1 to more than 12 mb. hr.$^{-1}$. In most cases gusty surface winds accompanied the passage of the katallobaric center and in some cases moderate rain occurred at the same time. Some of the pulses intensified and others weakened as they moved.

The katallobaric centers generally raced ahead of the cyclone producing wave-like deformations of the isobars and occasionally secondary low centers. The amoeboid fluctuations of the pressure field around the low center

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were apparently due to passage of the pulses across the system.

The first and most intense pulse of the group is illustrated in figure 12, showing the barograms for New Orleans (MSY), Maxwell Field (MXF), Atlanta (ATL) and Anderson, S. C. (AND) reconstructed from hourly observations and special reports of pressure jumps. The initial pressure minimum at MSY occurred with the passage of the cyclone south of the station. The pressure rose for 2 hours as the cyclone moved off then abruptly fell more than 9 mb. in 45 minutes. The increase in pressure following the minimum was almost as rapid as the fall.

The katallobaric center, which had been west of the Low raced northeastward through MXF, ATL, and AND almost without change of intensity until it was north of the cyclone. In North Carolina the pulse seemed to develop two weaker pulses which travelled toward the northeast and east-northeast respectively. At the same time the cyclone developed several secondaries which moved erratically through the Carolinas. The rapid pressure fall at ATL and AND was followed by an equally rapid rise, but only for a few minutes. Afterwards the pressure remained low. The pulse apparently had little effect on the central pressure of the Low which was deepening very slowly at this time (fig. 2). But it deformed the isobars north of the cyclone producing several elongated troughs (fig. 9).

## REFERENCES

1. A. H. Jones and C. L. Roe, "The Northern Gulf Low of February 14, 1953," *Monthly Weather Review*, vol. 81, No. 2, February 1953, pp. 47–52.
2. G. Reiss, "A Composite Analysis of Cyclonic Precipitation in the Eastern United States," *Technical Paper* No. 3, Contract No. Nonr-285(09), College of Engineering, Research Div., New York University, 1955, 35 pp.

# OPACITY OF THE SKY AFTER JULY 1953

I. ENGER AND S. FRITZ

U. S. Weather Bureau, Washington, D. C.

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## 1. INTRODUCTION

At 0500 MST, July 9, 1953, a subsidiary cone on the south flank of Mt. Spurr, about 80 miles west of Anchorage, Alaska, erupted a dark cloud of ash and vapor to a height of approximately 70,000 feet [1]. Vaucouleurs [2] has suggested that the spread of the volcanic dust be investigated by use of the pyrheliometric data in widely separated areas. A preliminary study by one of us [3] utilized data from three stations in the United States and evidence was given of a decrease in radiation for the 6-month period October 1953–March 1954. That investigation is described in greater detail here and is extended to Athens, Greece, Uccle, Belgium, and four stations in Japan.

## 2. DATA

The basic data at all stations are measurements of the intensity of the direct solar beam. At Lincoln, Nebr. and Blue Hill, Mass., the measurements are made with Eppley normal-incidence pyrheliometers. At Table Mountain, Calif., the more precise Smithsonian silver-disk and modified Ångström normal-incidence pyrheliometers are used. A silver-disk pyrheliometer is used frequently to check the Eppley instrument at Blue Hill. In Japan, silver-disk pyrheliometers constructed by the Japan Central Meteorological Observatory are used. A Kipp-Zonen pyrheliometer on a stand is used at Athens, while at Uccle two Linke-Feussner actinographs measure the solar radiation.

The average monthly values of the clear-sky radiation at a particular time of day or zenith distance were readily available at all stations except Uccle [4, 5, 6, 7]. The data for Uccle, kindly furnished us by Mr. R. Dogniaux, were the total amounts of radiation falling each half-hour regardless of sky condition. Values were extracted for those times when the percentage sunshine was 100. In order to determine the radiation at a particular airmass the times of observation were converted to airmass values. When this was done it became evident that more observations were available in the neighborhood of airmass 4.00 than at any other airmass value. On the large majority of days no observation was taken at exactly airmass 4.00, but some were made at higher airmass values and some at lower. A plot of log of radiation against airmass was made for each day. A smooth curve was drawn free-hand through these points and the value of radiation for airmass 4.00 was interpolated. It was apparent from the great variability within a single month that this procedure did not completely eliminate those days when high cirrus, smoke, haze, or fog affected the pyrheliometric measurements. Thus, monthly means computed from these values did not accurately estimate the clear-sky radiation. On the assumption that there should be at least one good observing day each month, the highest radiation value for the month was used as a measure of the monthly mean clear-sky radiation at Uccle.

At each station monthly "averages" were secured. The "average" is defined as the weighted arithmetic mean of the monthly radiation values for the period of record up through 1952, the weights being the number of observations in the month. An exception was made at Blue Hill. There the instructions are that observations should be taken only when clouds do not interfere with the measurements. This is a somewhat subjective matter and undoubtedly introduces some fluctuations into the data. At Blue Hill, a new observer reported for duty near the end of 1951, and has taken observations there since the beginning of 1952. He has chosen only the "clearest" skies, so that the "average" appropriate to his observations is apparently about 11 percent higher than the "average" for the period 1934–51. To adjust for this, the monthly radiation values after December 1951 were divided by 1.11 and these new values were used in all subsequent work. The "average" at Blue Hill was then computed by the method used at the other stations.

The departures of the average monthly radiation from the monthly "averages" were computed and expressed as percentages of the "average"; these are hereafter called "D values." The results for the entire period of record are listed in table 1 and the values from 1950–54 are shown in figure 1. The small numerals over the curves are the number of observations made during the month.

Since results from independent sources are more reliable, D values at some of the stations were tested for interdependence. Correlation coefficients between each two of the three United States stations and between each two of the four Japanese stations are shown in table 2. The period 1934 through 1952 was used in the United States and 1939 through 1952 in Japan. None of the

TABLE 1.—*Departure of monthly solar radiation intensity from monthly "average" expressed as a percentage of "average"*

**BLUE HILL OBSERVATORY, MILTON, MASS.**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1934 | −13 | 1 | −10 | −3 | −7 | 10 | 17 | −1 | 0 | 3 | 0 | 8 |
| 1935 | 6 | 1 | 2 | 17 | 0 | 11 | 22 | 14 | 3 | 1 | −6 | 4 |
| 1936 | 5 | 1 | −16 | 10 | 3 | −3 | −15 | 23 | −11 | 1 | 8 | 7 |
| 1937 | −3 | 5 | 7 | 11 | 0 | 23 | 6 | 1 | 5 | 7 | 5 | −1 |
| 1938 | −8 | 6 | −1 | 17 | 32 | 14 | 41 | ------ | 11 | −14 | −18 | −10 |
| 1939 | −9 | 4 | 0 | −6 | −2 | −3 | 0 | −5 | −9 | 1 | −5 | 6 |
| 1940 | −3 | −4 | 6 | 7 | −6 | 5 | −16 | 26 | −6 | 2 | −2 | 8 |
| 1941 | 7 | 4 | 10 | −6 | −4 | −26 | −8 | −5 | 11 | 4 | −3 | 4 |
| 1942 | −7 | −3 | −2 | −20 | −16 | −19 | −22 | −1 | −18 | −3 | 7 | −10 |
| 1943 | 6 | −4 | 4 | 5 | −1 | −27 | 5 | −12 | 10 | −2 | 0 | −3 |
| 1944 | −9 | −4 | 10 | 6 | −23 | −6 | −9 | 5 | 3 | 7 | −2 | −2 |
| 1945 | 8 | 0 | 26 | 3 | 2 | 8 | −8 | −1 | −2 | 7 | −5 | 3 |
| 1946 | 2 | −6 | −17 | −2 | −1 | −7 | −1 | 6 | −9 | −5 | 5 | 3 |
| 1947 | −6 | 1 | −3 | 7 | 8 | −6 | 3 | −17 | 4 | −7 | 9 | 6 |
| 1948 | 9 | 2 | 5 | 11 | 6 | −7 | 6 | −13 | −10 | −8 | 6 | 0 |
| 1949 | 8 | −1 | 10 | −11 | −18 | 12 | 6 | −6 | 10 | 5 | −2 | 4 |
| 1950 | 0 | 6 | 12 | 7 | 11 | 0 | 7 | 9 | 11 | −8 | −13 | −5 |
| 1951 | 0 | 3 | 2 | −4 | 6 | −6 | −5 | 7 | −1 | −7 | 15 | −22 |
| 1952 | −2 | −5 | −6 | −1 | −1 | 3 | 1 | 22 | 0 | −4 | −4 | −7 |
| 1953 | −3 | −5 | 6 | −4 | ------ | −1 | 10 | −14 | −5 | −11 | −24 | −8 |
| 1954 | −9 | −16 | −11 | 5 | −5 | −2 | −3 | 13 | −7 | −4 | −11 | −3 |

**TABLE MOUNTAIN, CALIF.**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1926 | 0 | 3 | −2 | −2 | −1 | −2 | 0 | 1 | 1 | 0 | −1 | 0 |
| 1927 | −1 | 0 | −1 | 1 | 1 | −1 | 0 | −1 | 1 | −1 | 0 | 1 |
| 1928 | 1 | −1 | −1 | 1 | ------ | 1 | 1 | 0 | 1 | −1 | 1 | 1 |
| 1929 | 0 | 2 | 0 | 0 | −1 | 0 | −5 | −4 | −1 | −3 | −1 | −1 |
| 1930 | −4 | −1 | −2 | 1 | 0 | 1 | 0 | 0 | −1 | 1 | 0 | 1 |
| 1931 | 1 | −3 | 0 | −1 | 1 | −1 | −5 | −5 | 1 | 0 | 0 | 1 |
| 1932 | 0 | −1 | 0 | 0 | 0 | −1 | −1 | −2 | −5 | 0 | −1 | −1 |
| 1933 | −1 | 0 | 0 | −1 | −1 | 0 | 0 | 0 | 1 | −1 | 0 | −1 |
| 1934 | 0 | 0 | −2 | 2 | 0 | −1 | −1 | −5 | 0 | −1 | 0 | 3 |
| 1935 | 0 | 0 | 2 | −1 | −2 | 0 | 2 | 1 | −3 | 2 | 2 | 1 |
| 1936 | 0 | 2 | 0 | 2 | 2 | 1 | −3 | 0 | 1 | 0 | 0 | 0 |
| 1937 | 0 | 3 | 1 | 1 | −3 | −1 | 0 | −2 | 0 | 0 | −1 | 1 |
| 1938 | 0 | 1 | −1 | 0 | 0 | −3 | −2 | −2 | −1 | 0 | 2 | 1 |
| 1939 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | −1 | 1 | 2 | 0 | 0 |
| 1940 | 4 | 0 | 2 | 1 | 0 | −1 | 1 | −2 | 0 | 0 | 2 | 0 |
| 1941 | 2 | 0 | −1 | 1 | 1 | −1 | −1 | 0 | 0 | 2 | 0 | 1 |
| 1942 | 0 | 1 | 1 | 1 | 2 | 1 | 1 | −3 | 1 | −1 | −2 | −1 |
| 1943 | −1 | 1 | 0 | −1 | 2 | 1 | 0 | 1 | −2 | 1 | 0 | −1 |
| 1944 | 0 | 1 | 1 | 1 | 0 | 1 | 2 | 3 | 2 | 0 | 0 | 1 |
| 1945 | −1 | 0 | ------ | ------ | 2 | 0 | 2 | 5 | 1 | 0 | 0 | −1 |
| 1946 | 0 | −1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 2 | 0 | 3 |
| 1947 | 0 | 0 | 0 | −1 | −1 | −1 | 1 | 3 | 0 | 0 | 0 | 1 |
| 1948 | 0 | 2 | 1 | 2 | 2 | 1 | 2 | 3 | 1 | 0 | 0 | −1 |
| 1949 | 2 | 1 | 1 | 2 | −1 | 1 | 0 | 3 | 3 | 0 | 0 | 1 |
| 1950 | 2 | −2 | 2 | −1 | 1 | 1 | −2 | −2 | 0 | 1 | −1 | 0 |
| 1951 | 0 | −1 | −1 | 1 | −3 | 1 | 0 | 2 | 1 | 1 | 0 | 1 |
| 1952 | 0 | −2 | 0 | −9 | −1 | 0 | −2 | −2 | −3 | 0 | 0 | −1 |
| 1953 | −1 | 0 | 0 | −1 | 1 | 1 | −4 | −1 | −2 | −3 | −2 | −1 |
| 1954 | −3 | −2 | −3 | −3 | 0 | 0 | −4 | −1 | 1 | 0 | −1 | 0 |

**LINCOLN, NEBR.**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1917 | ------ | ------ | 12 | −18 | ------ | 13 | 7 | 15 | −8 | −3 | −5 | −3 |
| 1918 | ------ | 0 | −4 | 9 | −1 | 2 | −2 | 7 | 7 | 6 | 3 | ------ |
| 1919 | 0 | 3 | 3 | 12 | 7 | −3 | −13 | 14 | 0 | 1 | 8 | 6 |
| 1920 | −5 | −9 | 3 | −13 | ------ | 8 | 3 | −5 | 12 | 6 | 9 | 3 |
| 1921 | 6 | 6 | −2 | 0 | 8 | 9 | 0 | −1 | −2 | 6 | 4 | 3 |
| 1922 | −10 | −1 | 4 | 3 | 13 | −9 | −4 | −3 | 0 | −1 | 3 | −1 |
| 1923 | 0 | −2 | 4 | −21 | 13 | 3 | 4 | 10 | 7 | 12 | 2 | 11 |
| 1924 | 3 | −8 | 0 | 6 | ------ | −8 | ------ | 7 | 7 | 9 | 1 | 6 |
| 1925 | 3 | −8 | 3 | ------ | 0 | 8 | −4 | −7 | 4 | 17 | 3 | 6 |
| 1926 | 3 | 3 | 12 | 0 | −6 | 4 | −6 | 0 | 11 | 7 | −3 | ------ |
| 1927 | 1 | −2 | 12 | 15 | 8 | 6 | 7 | 2 | 1 | 5 | 1 | −3 |
| 1928 | 5 | 6 | 2 | 6 | 2 | 18 | 1 | 14 | 1 | −4 | 4 | −10 |
| 1929 | 2 | −11 | 5 | 7 | 6 | 7 | −8 | −13 | −19 | −1 | −2 | ------ |
| 1930 | 0 | −7 | 5 | −4 | 8 | 10 | −8 | −22 | 2 | ------ | −2 | 4 |
| 1931 | −3 | −3 | 6 | 2 | −7 | −4 | −2 | 6 | −8 | 7 | 4 | 6 |
| 1932 | 3 | −1 | 2 | ------ | 2 | 1 | 10 | 14 | 5 | 6 | 4 | −4 |
| 1933 | −3 | −1 | 2 | −1 | −4 | 0 | 3 | 8 | 4 | 3 | 0 | 3 |
| 1934 | 0 | −7 | 10 | −13 | −3 | 3 | 2 | −1 | 8 | −5 | 1 | 3 |
| 1935 | 6 | −3 | 4 | 4 | 16 | 7 | −4 | 7 | 7 | 9 | 8 | 7 |
| 1936 | 6 | −1 | 2 | 1 | 4 | 13 | 12 | 3 | 1 | 13 | −3 | −3 |
| 1937 | 0 | −16 | 16 | 62 | −3 | 2 | −1 | 15 | 1 | 3 | 10 | 8 |
| 1938 | 6 | 3 | −6 | 14 | 12 | 1 | ------ | −27 | 0 | 8 | 5 | 14 |
| 1939 | 11 | 6 | 7 | 9 | 3 | −10 | −2 | 12 | 3 | −4 | −1 | −3 |
| 1940 | 5 | 1 | ------ | 15 | ------ | −6 | ------ | 14 | ------ | 5 | ------ | ------ |
| 1941 | ------ | ------ | ------ | ------ | ------ | −15 | 2 | −7 | 6 | 15 | 0 | 3 |
| 1942 | 3 | −2 | 12 | −1 | −10 | ------ | ------ | −44 | −3 | −7 | −10 | 1 |
| 1943 | −2 | −7 | −9 | −1 | 6 | 1 | 3 | −5 | 4 | 0 | ------ | ------ |
| 1944 | ------ | −7 | 9 | 5 | 2 | 1 | 2 | −2 | −7 | 17 | 3 | 3 |
| 1945 | 3 | ------ | −5 | 2 | 0 | −6 | −1 | −2 | 1 | 2 | −1 | 1 |
| 1946 | −5 | −8 | 0 | −9 | ------ | −6 | −7 | 5 | 15 | −1 | −11 | 0 |
| 1947 | 1 | −3 | −3 | −6 | −4 | 12 | −3 | −10 | −13 | −3 | 5 | 1 |
| 1948 | −2 | −1 | −2 | 10 | 2 | −4 | −4 | −12 | −5 | −11 | −3 | 3 |
| 1949 | −2 | −6 | ------ | 0 | −3 | −10 | −13 | −1 | −6 | −5 | −9 | −5 |
| 1950 | −2 | −8 | 11 | 1 | −11 | −10 | 2 | 1 | −16 | −8 | 0 | 0 |
| 1951 | −5 | −15 | −3 | 21 | 3 | −13 | 3 | 5 | 0 | −5 | −2 | 3 |
| 1952 | −8 | −6 | −8 | −6 | 10 | −10 | 0 | −7 | −15 | −15 | −8 | 0 |
| 1953 | −9 | ------ | −5 | ------ | −3 | 0 | −7 | −2 | −6 | −13 | −9 | −3 |
| 1954 | −6 | −10 | −26 | −2 | 8 | −9 | −15 | 13 | −8 | 2 | −5 | 0 |

**ATHENS, GREECE**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1952 | −2 | 2 | −7 | −3 | 4 | 3 | 2 | 0 | −3 | 4 | 2 | 4 |
| 1953 | 7 | 0 | 6 | 0 | −5 | 2 | 4 | 0 | 3 | −6 | 3 | −10 |
| 1954 | −1 | 0 | −2 | 4 | 2 | −4 | −3 | 1 | 0 | −4 | −5 | 5 |
| 1955 | −1 | −3 | −1 | 1 | −2 | −1 | −4 | −2 | 0 | 7 | ------ | ------ |

**UCCLE, BELGIUM**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1949 | 19 | 13 | 0 | −3 | 8 | 18 | 29 | 10 | 2 | −1 | 4 | 5 |
| 1950 | 17 | 6 | −4 | −15 | −3 | 0 | 6 | 13 | 5 | −4 | −16 | −28 |
| 1951 | −40 | 0 | −15 | 22 | −4 | 3 | 6 | −15 | −3 | 20 | 19 | 4 |
| 1952 | −8 | −6 | 20 | 14 | 4 | 4 | −4 | 5 | −11 | −5 | 6 | 0 |
| 1953 | 3 | −7 | 22 | −7 | −3 | −11 | 19 | −12 | −2 | −1 | −19 | −18 |
| 1954 | 18 | −6 | −23 | −11 | −4 | −15 | −55 | −21 | 13 | −8 | −11 | 10 |

**FUKUOKA, JAPAN**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1939 | 2 | 0 | −5 | 2 | 3 | −2 | −2 | −4 | 1 | −3 | −3 | 2 |
| 1940 | 6 | 4 | ------ | 5 | ------ | 2 | 0 | 0 | 2 | 0 | −2 | −4 |
| 1941 | ------ | 3 | 0 | 4 | 4 | 6 | −3 | −10 | 4 | 4 | 5 | 4 |
| 1942 | 7 | −5 | −7 | −3 | −2 | −2 | 1 | ------ | −1 | −1 | 3 | −13 |
| 1943 | 2 | 8 | 6 | 2 | −1 | −5 | ------ | 1 | −4 | −5 | −1 | 0 |
| 1944 | −15 | 2 | 2 | 1 | −9 | −4 | 12 | 3 | −2 | 10 | 2 | ------ |
| 1945 | −14 | 3 | 0 | −10 | 5 | −3 | 7 | 1 | 0 | 4 | 2 | ------ |
| 1946 | 7 | 1 | 6 | 1 | 8 | 12 | 5 | ------ | −11 | −2 | 11 | 11 |
| 1947 | ------ | 8 | 11 | 5 | −8 | 2 | ------ | −6 | 10 | 8 | −4 | 15 |
| 1948 | 8 | −1 | 3 | 5 | 0 | 3 | ------ | 1 | −1 | −2 | −5 | 0 |
| 1949 | 0 | 2 | −1 | 11 | 5 | −8 | 4 | −3 | 1 | −11 | 4 | −13 |
| 1950 | −5 | 7 | 2 | −11 | 2 | −8 | −6 | 5 | 9 | −1 | 0 | ------ |
| 1951 | 1 | −19 | −7 | 3 | −1 | −3 | 8 | 3 | ------ | −2 | −3 | 2 |
| 1952 | 4 | ------ | −5 | 3 | 0 | 6 | −13 | −1 | 1 | 1 | −3 | −8 |
| 1953 | −5 | ------ | 4 | −1 | −1 | 13 | −6 | ------ | −3 | 1 | 4 | −9 |
| 1954 | ------ | −11 | −1 | 1 | 0 | 8 | ------ | −6 | −7 | 1 | −9 | −2 |

**MATSUMOTO, JAPAN**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1939 | 4 | 7 | 2 | −4 | 6 | −5 | −2 | 7 | 3 | 2 | −4 | 3 |
| 1940 | −2 | 2 | ------ | 3 | ------ | 1 | 7 | 0 | −1 | 2 | 5 | 2 |
| 1941 | −1 | 1 | −2 | 3 | 3 | −2 | 5 | −4 | ------ | −1 | −2 | −1 |
| 1942 | 3 | −4 | −1 | 3 | −8 | 4 | −2 | ------ | −3 | −4 | 5 | 1 |
| 1943 | 3 | 3 | −4 | 2 | −3 | −2 | 3 | −2 | −13 | 5 | 1 | 7 |
| 1944 | 2 | 1 | 5 | ------ | −11 | −3 | −2 | 3 | 0 | 3 | −2 | −1 |
| 1945 | −2 | 1 | 2 | −2 | 4 | 2 | 13 | −3 | 2 | 6 | 7 | 2 |
| 1946 | 0 | 1 | 3 | −1 | −1 | 2 | 3 | 4 | 2 | 4 | 1 | 5 |
| 1947 | 2 | 1 | 1 | 0 | −1 | 4 | −4 | 0 | 5 | 4 | 4 | 2 |
| 1948 | 6 | 2 | 1 | −3 | 3 | 1 | 7 | 4 | −1 | −3 | 4 | 3 |
| 1949 | −4 | ------ | ------ | 4 | 4 | 5 | 4 | 2 | 2 | 3 | 1 | 6 |
| 1950 | −5 | 2 | 1 | 0 | 5 | 0 | −1 | −8 | −2 | −1 | −6 | 0 |
| 1951 | −1 | 1 | −1 | 1 | −3 | 1 | 2 | −7 | 1 | −3 | −2 | −7 |
| 1952 | 4 | −5 | −5 | −4 | 6 | 2 | −6 | 0 | −3 | 1 | 0 | −4 |
| 1953 | −4 | −4 | 2 | −2 | 0 | −3 | −3 | −6 | −3 | −4 | −5 | −8 |
| 1954 | 1 | −7 | −4 | −4 | −6 | −2 | 2 | −2 | −2 | −2 | −5 | −5 |

**SHIMIZU, JAPAN**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1939 | 2 | 3 | 3 | 1 | −1 | 0 | −1 | −2 | 0 | 3 | −2 | 2 |
| 1940 | −4 | 2 | ------ | 5 | ------ | 3 | −9 | 6 | 1 | 2 | 2 | 8 |
| 1941 | −1 | 0 | −6 | −4 | −8 | −8 | 2 | 5 | 5 | 6 | 0 | 0 |
| 1942 | 5 | −1 | ------ | 0 | 0 | ------ | −2 | ------ | −3 | 1 | −7 | −1 |
| 1943 | 2 | 1 | 3 | 5 | −4 | −13 | 0 | −4 | −3 | −4 | 3 | −3 |
| 1944 | 9 | ------ | 2 | 3 | ------ | ------ | −1 | 5 | −11 | −2 | ------ | −6 |
| 1945 | −2 | 1 | 0 | −3 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ |
| 1946 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | −5 | 7 | 3 |
| 1947 | −2 | ------ | 4 | 1 | 1 | −3 | 2 | −1 | 0 | 3 | 0 | 1 |
| 1948 | 1 | −4 | 3 | 7 | 1 | 4 | ------ | ------ | 4 | −1 | 2 | −1 |
| 1949 | 5 | −4 | 1 | −1 | 7 | −6 | 9 | −2 | 5 | 0 | 3 | 2 |
| 1950 | −3 | 2 | 7 | −6 | 1 | 2 | 7 | −6 | −3 | −6 | −1 | 0 |
| 1951 | 0 | −1 | −6 | −2 | −1 | 2 | 1 | 0 | 4 | 1 | −3 | −1 |
| 1952 | 0 | −5 | 3 | 3 | −1 | 2 | 3 | 2 | 3 | 1 | −8 | −3 |
| 1953 | −2 | −1 | −2 | −10 | −6 | −6 | ------ | −8 | −8 | −5 | −5 | −5 |
| 1954 | −5 | −9 | −4 | −6 | 3 | −1 | −1 | −8 | −3 | −2 | −5 | −11 |

**TOKYO, JAPAN**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1939 | 2 | 6 | 11 | 4 | ------ | 1 | −6 | 14 | 3 | −1 | 12 | 11 |
| 1940 | 4 | 15 | ------ | 5 | ------ | −8 | 4 | 26 | 10 | 10 | −4 | 4 |
| 1941 | 1 | 11 | 4 | 2 | 3 | 9 | 8 | −9 | 11 | 2 | −4 | −19 |
| 1942 | −1 | −2 | −3 | 2 | 1 | 5 | −8 | ------ | −2 | −5 | 4 | 3 |
| 1943 | 11 | 0 | 3 | 10 | −2 | −8 | 2 | 6 | 3 | 1 | −4 | 5 |
| 1944 | 5 | 11 | 12 | 5 | 7 | −4 | −1 | −4 | 0 | 12 | −8 | 4 |
| 1945 | 4 | 2 | 3 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ |
| 1946 | ------ | ------ | ------ | ------ | ------ | 10 | −8 | 0 | 4 | 8 | 6 | 5 |
| 1947 | −2 | 3 | 2 | −3 | 11 | ------ | 7 | −1 | 5 | 10 | −2 | 0 |
| 1948 | 1 | 2 | −1 | 2 | 12 | 2 | 1 | 14 | 8 | −2 | 6 | 7 |
| 1949 | 6 | −1 | 1 | 0 | 8 | 4 | 1 | ------ | −14 | 5 | 3 | 17 |
| 1950 | 7 | 7 | 8 | −14 | 26 | ------ | 3 | ------ | −1 | −12 | 0 | −1 |
| 1951 | −4 | −5 | −13 | 6 | 3 | 6 | ------ | −13 | −9 | 1 | 4 | −1 |
| 1952 | −11 | −8 | −2 | −3 | 2 | 5 | −11 | −9 | −4 | −2 | −2 | −13 |
| 1953 | −1 | −8 | −3 | −6 | −9 | ------ | ------ | 3 | 14 | −8 | 2 | −3 |
| 1954 | −5 | −14 | −4 | −3 | 2 | ------ | ------ | ------ | 3 | −10 | −7 | 7 |

**JAPAN**

(Mean of the four stations above)

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1939 | 2.5 | 4.0 | 2.8 | 0.8 | 2.7 | −1.5 | −3.0 | 4.8 | 1.8 | 0.3 | 0.8 | 4.5 |
| 1940 | 1.0 | 5.8 | ------ | 4.5 | ------ | −.5 | .5 | 8.0 | 3.0 | 3.5 | .3 | 2.5 |
| 1941 | −.3 | 2.3 | −1.0 | 1.3 | .5 | 1.3 | 3.0 | −4.5 | 6.7 | 2.8 | −.2 | −4.0 |
| 1942 | 3.5 | −3.0 | −3.7 | .5 | −2.2 | 2.3 | −2.7 | ------ | −2.2 | −2.2 | 1.3 | −2.5 |
| 1943 | 4.5 | 3.0 | 2.0 | 4.8 | −2.5 | −7.0 | 1.7 | .3 | −4.2 | −.7 | −.2 | 2.3 |
| 1944 | .3 | 4.7 | 5.3 | 3.0 | −4.3 | −3.7 | 2.0 | 1.8 | −3.2 | 5.8 | −2.7 | −1.0 |
| 1945 | −3.5 | 1.8 | 1.3 | −3.0 | 4.5 | −.5 | 10.0 | −1.0 | 1.0 | 5.0 | 4.5 | 2.0 |
| 1946 | 3.5 | 1.0 | 4.5 | 0.0 | 3.5 | 8.0 | 0.0 | 2.0 | −1.7 | 1.3 | 6.3 | 6.0 |
| 1947 | −.7 | 4.0 | 4.5 | .8 | .8 | 1.0 | 1.7 | −2.0 | 5.0 | 6.3 | −.5 | 4.5 |
| 1948 | 4.0 | −.2 | 1.5 | 2.8 | 4.0 | 2.5 | 4.0 | 6.3 | 2.5 | −2.0 | 1.8 | 2.3 |
| 1949 | 1.8 | −1.0 | .3 | 3.5 | 6.0 | −1.2 | 4.5 | −1.0 | −1.5 | −.7 | 2.8 | 3.0 |
| 1950 | −1.5 | 4.5 | 4.5 | −7.7 | 8.5 | −2.0 | .8 | −3.0 | .8 | −5.0 | −1.7 | −.3 |
| 1951 | −1.0 | −6.0 | −6.7 | 2.0 | −.5 | 1.5 | 3.7 | −4.2 | −1.3 | −.7 | −1.0 | −1.7 |
| 1952 | −.7 | −6.0 | −2.2 | −.2 | 1.8 | 3.8 | −6.7 | −2.0 | −.7 | .3 | −3.2 | −7.0 |
| 1953 | −3.0 | −4.3 | .3 | −4.7 | −4.0 | 1.3 | −4.5 | −3.7 | 0.0 | −4.0 | −1.0 | −6.2 |
| 1954 | −3.0 | −10.2 | −3.2 | −3.0 | −.2 | 1.7 | .5 | −5.3 | −2.2 | −3.2 | −6.5 | −2.7 |

correlations between stations in the United States is significant at the 5 percent level, while all the correlations between Japanese stations are significant beyond the 1 percent level.

The results indicate that the D values at the three stations in the United States are usually independent but that there may be some slight interdependence between the stations in Japan. The United States stations are more than 1,000 miles from each other, whereas the distance between Japanese stations ranges from approximately 100 to 600 miles. Therefore, the D values at the four Japanese stations were averaged to secure one value, which can be considered as an estimate of the amount of clear sky radiation over Japan. These averages are listed in table 1 and plotted in figure 1.

Although no correlations were made involving Athens, Greece or Uccle, Belgium it appears reasonable to assume, especially in view of the low correlations in table 2, that the D values at these two stations are independent of each other as well as of the stations in Japan and the United States. Thus there are six relatively independent series of radiation values: Blue Hill, Lincoln, Table Mountain, Japan, Athens, and Uccle.

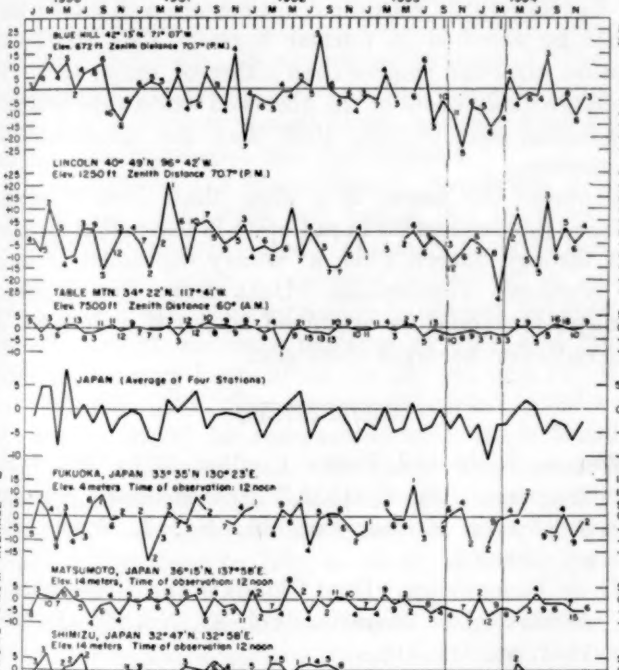



FIGURE 1.—Solar radiation intensity—departure from "average". (The small numerals over curves are the number of observations.)

TABLE 2.—*Correlation coefficients between departures from "average" radiation.*

| | Lincoln | Table Mountain | Matsumoto | Shimizu | Tokyo |
|---|---|---|---|---|---|
| Blue Hill | 0.10 | 0.12 | | | |
| Lincoln | | −.03 | | | |
| Fukuoka | | | 0.30 | 0.39 | −0.24 |
| Matsumoto | | | | .35 | .34 |
| Shimizu | | | | | .39 |

Because of the rather large variability of the D values, 6-month running means were computed for all consecutive 6-month periods for which data are available. There is nothing especially significant about the choice of a 6-month period, it simply appeared to be a reasonable length to use to reduce the variability of the monthly D values. The 6-month running means for 1950 to 1954 are shown in figure 2; the points are plotted at the fourth month of the 6-month period. The dashed portions of the curves cover periods when less than six consecutive months of data were available. In these cases linear interpolation was used to estimate the values for the missing months and 6-month

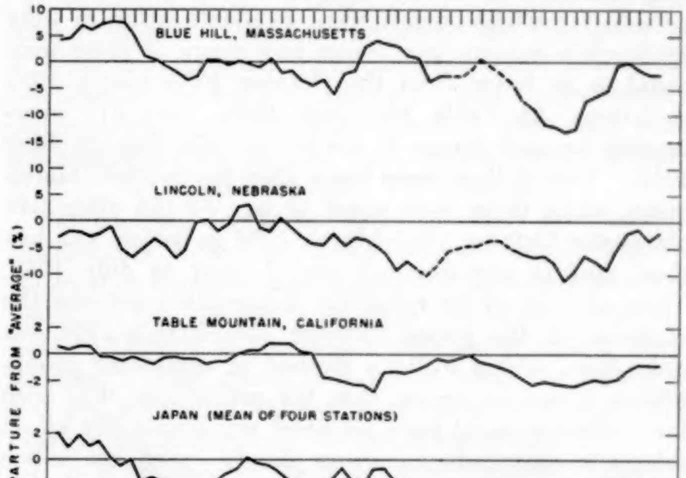



FIGURE 2.—Six-month running means of solar radiation intensity. Dashed portions are based, in part, on interpolated values. (Note different scales for Table Mountain and Japan.)

averages were then computed. Interpolated values and 6-month averages computed by using one or more interpolated values are excluded from the analysis to be described below.

## 3. RESULTS

Figure 1 shows that the radiation at the three stations in the United States was low after July 1953. All three stations were below "average" on August 1953 and continued so through March 1954. A study of table 1 shows that below "average" radiation for a period of eight months is rather unusual at any one station. It is highly unlikely that the simultaneous occurrence of low radiation at three independent stations for such a long period can be due to random fluctuations. Examination of the curves of the other stations plotted in figure 1 reveals no such readily apparent low radiation values although there is some tendency in that direction.

However, the smoothed values in figure 2 do show low radiation sometime after July 1953 at all six places. The value plotted at January 1954, which is the mean for the period October 1953 through March 1954, appears to be low on all six curves. To test this, a comparison was made between this 6-month mean and means prior to July 1953. The results are shown in table 3. In the third column is listed the number of consecutive 6-month periods for which means were available prior to July 1953, while column four shows how many of these were equal to or lower than the October 1953–March 1954 radiation. At Table Mountain there were 312 overlapping 6-month means in the period 1926 through June 1953. Two of these were lower than the October–March mean, while three were equal to it. At the other five places the October 1953–March 1954 radiation was less than that in any 6-month period prior to July 1953. Thus, at each of six relatively independent stations the radiation in the period October 1953–March 1954 was quite low. Using Fisher's method of combining probabilities it can be shown that the probability that such low radiation could have occurred simultaneously at six relatively independent stations simply by chance is less than one in ten thousand.

Comparison of the October 1953–March 1954 mean with 6-month means after July 1953 can be made by examination of figure 2. The October 1953–March 1954 mean (plotted at January 1954) is lower than any 6-month mean after July 1953 on four of the six curves; at Table Mountain it is lower than all except the November 1953–April 1954 mean; while at Uccle it is lower than all except the November 1953–April 1954 and February–July 1954 means. It may be noted that some of the dashed portions of the Uccle curve are considerably lower than the October 1953–March 1954 value. However, the dashed portions are based on less than six monthly values and are not strictly comparable with the 6-month means.

The cause of the low radiation is speculative. Arakawa and Tsutsumi [8] also noted a decrease in radiation in Japan. They hypothesize that thermonuclear tests may

TABLE 3.—*Comparison of 6-month means of radiation in period prior to July 1953 with average for October 1953–March 1954 period*

| | Period of record | Number of 6-month means | Number ≤October 1953–March 1954 |
|---|---|---|---|
| Blue Hill, Mass. | 1934 to June 1953 | 203 | 0 |
| Lincoln, Nebr. | 1917 to June 1953 | 307 | 0 |
| Table Mountain, Calif. | 1926 to June 1953 | 312 | 5 |
| Japan | 1939 to June 1953 | 165 | 0 |
| Athens, Greece | 1952 to June 1953 | 13 | 0 |
| Uccle, Belgium | 1949 to June 1953 | 54 | 0 |

be responsible for the observed decreases in radiation but also state that these tests can not be said to be the unique cause of the radiation decrease. There is no conclusive evidence that nuclear tests decrease solar radiation on a worldwide basis. For example, no definite decrease occurred at all three stations in the United States following the November 1952 tests. Explosive volcanoes, on the other hand, have unquestionably reduced solar radiation markedly on occasions in the past. The decreases in radiation following the Krakatoa (1883) and Katmai (1912) volcanic eruptions are well known and cannot be ascribed to nuclear bursts. The Mt. Spurr eruption, although smaller than either of these, seems to be a more likely cause of the observed worldwide decrease in radiation after October 1953 than the thermonuclear experiments.

Whatever the cause, it is clear that there is strong evidence for a reduction in radiation in the period October 1953 through March 1954, at widely separated areas in the Northern Hemisphere. Data from the Southern Hemisphere should be examined to see if a decrease in solar radiation occurred there also.

## REFERENCES


1. Werner Juhle and Henry Coulter, "The Mt. Spurr Eruption, July 9, 1953," *Transactions, American Geophysical Union*, vol. 36, No. 2, April 1955, pp. 199–202.
2. G. de Vaucouleurs, "Dust Clouds in the Stratosphere," *Meteorological Magazine*, vol. 83, No. 988, October 1954, pp. 311–312.
3. S. Fritz, "Opacity of the Atmosphere after July 1953," *Meteorological Magazine*, vol. 85, No. 1006, April 1956, pp. 110–112.
4. U. S. Weather Bureau, *Monthly Weather Review*, 1917-1949, Washington, D. C.
5. U. S. Weather Bureau, *Climatological Data, National Summary*, 1950–1954, Washington, D. C.
6. Japan, Central Meteorological Observatory, *Geophysical Review*, 1939–1954, Tokyo, Japan.
7. Greece, National Observatory of Athens, *Monthly Climatological Bulletin of the Meteorological Institute*, January 1952–October 1955, Athens, Greece.
8. H. Arakawa, and K. Tsutsumi, "A Decrease in the Normal-Incidence Radiation Values for 1953 and 1954 and Its Possible Cause," *The Geophysical Magazine* (Japan), vol. 27, No. 1, January 1956, pp. 205–208.

# THE WEATHER AND CIRCULATION OF AUGUST 1956[1]

## A Marked Reversal in Hurricane Activity from August 1955

JAMES F. ANDREWS

Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

### 1. MID-SUMMER PERSISTENCE FOLLOWING AN EARLY-SUMMER REVERSAL

In June 1956 [1] the large-scale circulation features controlling the weather in the United States were two troughs, one near either coast of North America, separated by a stronger than normal ridge lying north-south over mid-continent. During July [2] a blocking surge, which had been centered over northern Canada in June, extended westward to Alaska and eastward to Greenland. This was accompanied by retrogression of the major troughs and ridges and a southward shift of the westerly wind belt in eastern North America and the Atlantic.

Comparison of the mean 700-mb. circulation patterns for July (see fig. 2 of [2]) and August (fig. 1) shows them to be highly intercorrelated. The magnitude of this persistence in circulation is expressed statistically in table 1, which shows that the correlation coefficient between the 700-mb. height anomaly patterns of July and August 1956, in the area from 30° N. to 50° N., and 70° W. to 130° W., was +.76. The area was restricted in order that the results might be comparable with those found by Namias in a previous study for the period from 1942–50 [3]. This unusually high correlation is even more interesting in view of the pronounced reversal in pattern which occurred from June to July, as shown in the first column of table 1.

The weather in the United States, closely related as it is to the mid-tropospheric circulation, similarly exhibited very little change from July to August 1956. Perhaps this is best seen by comparing figures 2 and 3, which show the observed temperature and precipitation anomaly classes for these two months. Statistical measures of this persistence are given in table 1. Of 100 stations evenly distributed around the country, 85 did not change by more than one class in temperature, while 43 remained in the same precipitation class. These figures represent considerably greater persistence than would be expected either by chance or from the 1942–50 average [3]. From June to July, by contrast, the reversal in temperature was striking. Precipitation however, displayed even greater persistence than is normally found between June and July (table 1). This is a bit unusual, in view of the reversal in circulation, and may reflect the discontinuous nature and randomness of precipitation patterns in the summer months, as well as the complexity of their relationship to mean summer circulation states.

### 2. WEATHER AND CIRCULATION IN THE UNITED STATES

#### TEMPERATURE

Temperatures in the United States during August averaged generally below normal in the northeastern quarter and western third of the country (fig. 2B and Chart I). In the Northeast the greatest departures observed were from 1° to 3° F. These are somewhat less than the 3° to 5° F. departures observed in the same region in July [2]. Northern Maine was the coolest area, with Caribou reporting its second coldest August of record, while daily minimum temperature records were established at Buffalo, N. Y., (Aug. 3), and Scranton, Pa. (Aug. 4).

The cool weather in the Northeast may be related to the monthly circulation pattern in several ways. Figure 1 shows that stronger than normal northwesterly flow prevailed at the 700-mb. level from the strong ridge over western Canada to the deep trough along eastern North America. Wind speeds in this area, where the jet stream was well defined at 700 mb., were above the normal, with greatest departures over the Lakes region (fig. 4).

The prevailing northwesterly flow was instrumental in steering the polar anticyclones that were associated with frequent outbreaks of cool Canadian air masses (Chart IX). The source region for much of this cool air, northwestern Canada and the Arctic region, was colder than the August normal, as can be seen in figure 5, which shows the mean thickness departures from normal for the layer 700 mb. to 1000 mb. Greatest mean virtual temperature

TABLE 1.—*Persistence measures of monthly mean anomalies in the United States during summer 1956*

| | June-July | | Change | July-August | |
|---|---|---|---|---|---|
| | 1956 | (1942–50) | | 1956 | (1942–50) |
| 700-mb. height (lag correlation) | −0.61 | 0.33 | 0 | 0.76 | 0.33 |
| Temperature (0 or 1 class change, percent) | 43 | 72 | 50 | 85 | 82 |
| Precipitation (0 class change, percent) | 45 | 35 | 33 | 43 | 34 |

[1] See Charts I–XVII following p. 328 for analyzed climatological data for the month.

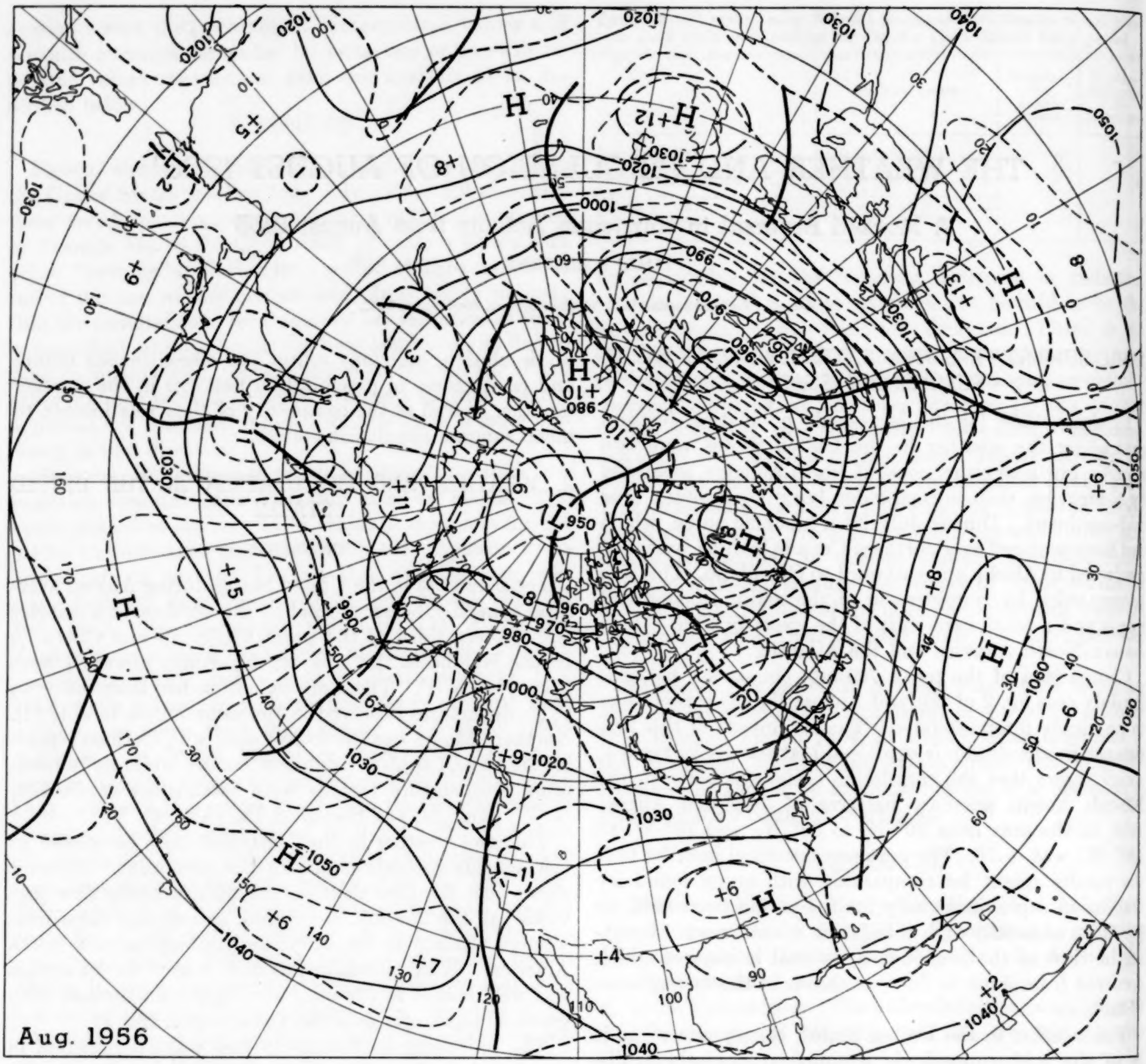



FIGURE 1.—Mean 700-mb. height contours and departure from normal (both in tens of feet) for August 1956. Deeper than normal troughs over eastern North America and western Europe were important features of the circulation.

departures (−8° F.) were found over southeastern Canada, another source region for much of the cool weather in the northeastern United States.

Temperatures also were below normal over most of the area from the Northern Plains to California (fig. 2B and Chart I), with maximum departures of 4° F. in central California. A few of the cities establishing daily minimum temperature records were: Helena, Mont.; Roseburg, Oreg.; Ely, Nev.; and Salt Lake City, Utah. The unseasonable coolness in the West was associated with below normal thickness values in the layer from 700 mb. to 1000 mb. (fig. 5) and was related to the prevalence of stronger than normal northerly flow at sea level (Chart XI). The greatest daily temperature departures in the Far West occurred early in the month when the mean trough along the Pacific coast was inland. For the five days ending August 5, temperatures in that area averaged as much as 15° F. below normal. For a detailed study of this cold period, the reader is referred to the article by McQueen and Thiel elsewhere in this issue [4].

The remainder of the nation, from the Central and Southern Plains through the South Atlantic States, was unseasonably warm, with maximum temperature departures of 4° F. in parts of Kansas and Oklahoma (fig. 2B

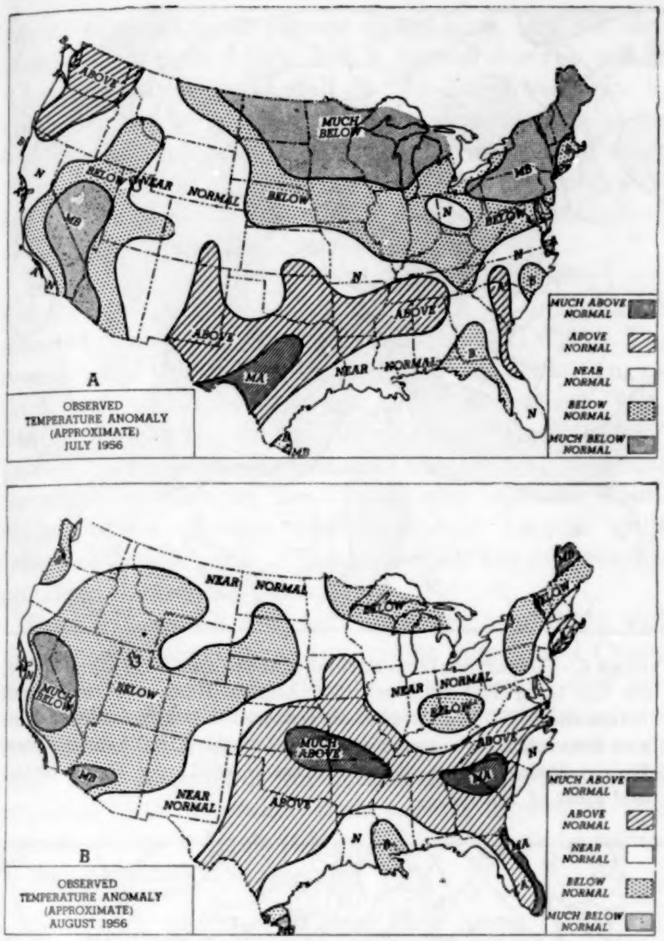



Figure 2.—Monthly mean surface temperature anomalies for (A) July 1956 and (B) August 1956. The classes above, below, and near normal occur on the average one-fourth of the time; much below and much above each normally occur one-eighth of the time.

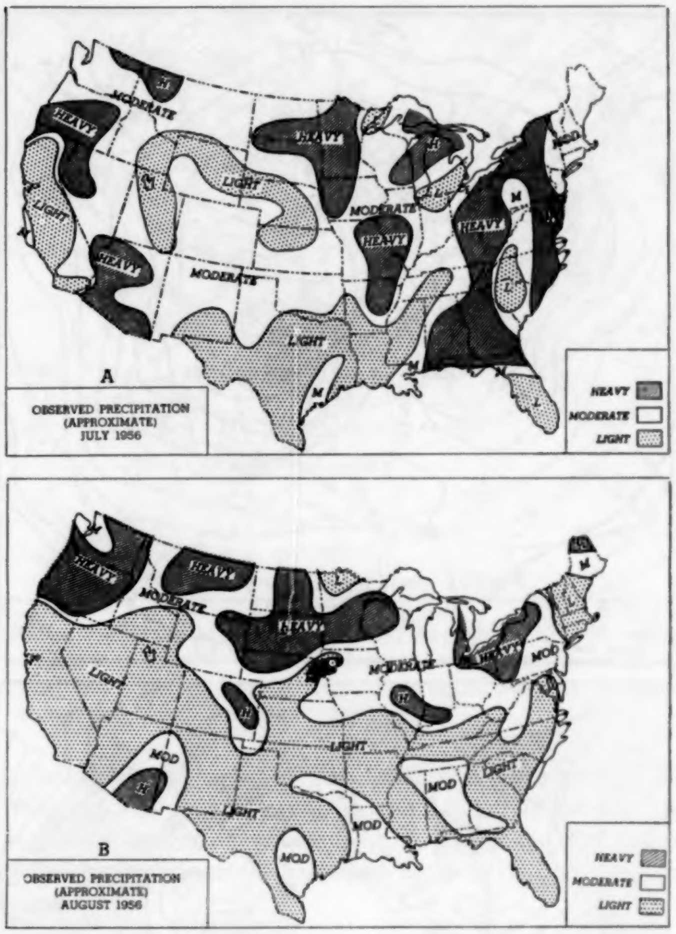



Figure 3.—Monthly precipitation anomalies for (A) July 1956 and (B) August 1956. The classes light, moderate, and heavy each normally occur one-third of the time.

and Chart I). Some of the daily maximum temperature records established were (in ° F.): Tulsa, Okla., 109 (5th and 6th); Dallas, Tex., 109 (5th); Concordia, Kans., 108 (16th); and Augusta, Ga., 104 (6th). Above normal temperatures in this area were related directly to the warm dynamic upper-level anticyclone centered over the Gulf States (fig. 1 and Charts XIII–XVI). Note that the area of abnormal surface warmth corresponds quite well to the area of above normal 700-mb. heights and to the region of positive thickness departures in the layer from 700 mb. to 1000 mb. (fig. 5). In addition, the belt of confluence, with stronger than normal wind speeds (fig. 4B), stretching from the Dakotas to the Middle Atlantic Coast (fig. 1), served to contain the cold air to the north and warm air to its south (fig. 2B and Chart I).

Shortly after mid-month, when the western Canadian ridge reached its greatest strength, a strong Polar anticyclone brought the coolest weather of the month to a wide area from the northern Plains to the Gulf and South Atlantic Coasts (see anticyclone track, Chart IX). In portions of the Central Plains and middle Mississippi Valley daily maximum temperatures fell into the 60's and 70's, where they previously had been reaching 100° F. Numerous daily minimum temperature records were established from the 19th to 23d, while some areas near the Gulf Coast experienced their lowest temperature ever recorded in August. Among the latter were Jackson, Miss., 54° F. (23d), and Baton Rouge, La., 60° F. (23d); while the 59° F. at Mobile, Ala. on the 22d was the lowest temperature ever observed there so early in the pre-fall season. Before arrival of the cooler air at Shreveport, La., temperatures had reached 100° F. or more on 15 consecutive days, an all-time record.

PRECIPITATION

Above normal amounts of precipitation were observed quite generally in the northern half of the United States, with portions of the Far Northwest, the Upper Mississippi Valley, and the eastern Great Lakes region receiving twice their normal amount (fig. 3B and Chart III). For some areas from the Dakotas to New York this was the wettest August in 16 years; while at Syracuse, N. Y., a fall of 8.41 inches was the greatest for any August.

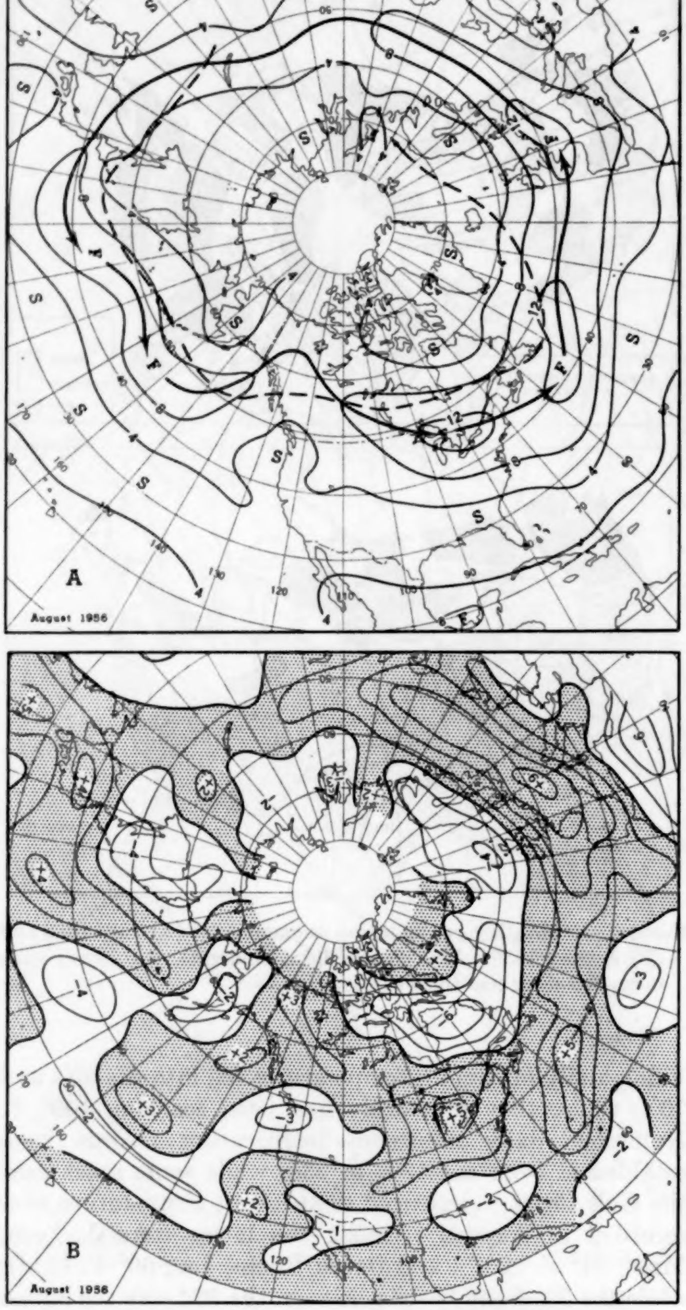



FIGURE 4.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for August 1956. Solid arrows in (A) indicate major axis of westerly jet, while dashed arrows show mean position of corresponding jet during August 1955. Positive wind speed anomalies in (B) are shaded. Fast westerly flow, south of normal, prevailed from the Great Lakes across the Atlantic through Europe and Central Asia.

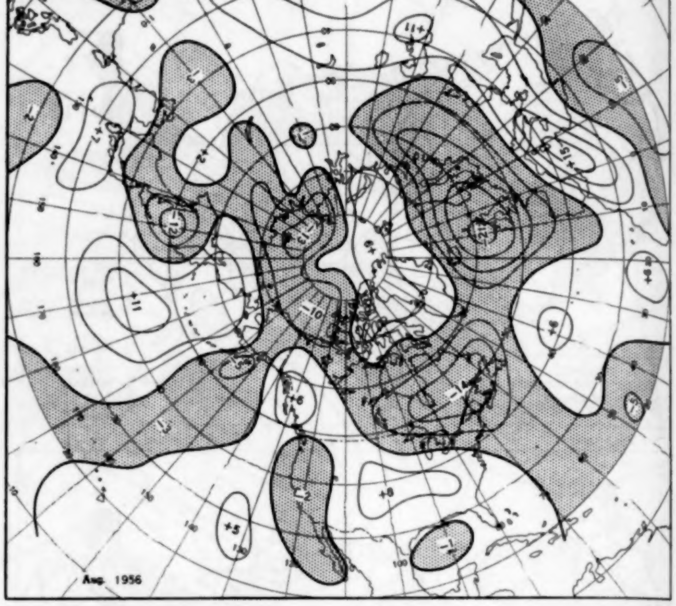



FIGURE 5.—Departure from normal of mean thickness (tens of feet) for the layer 700–1000 mb. for August 1956, with subnormal values shaded. Cold pool of air centered in southeastern Canada was associated with unseasonably cool weather in the northeastern United States. Note also the extreme cold over Great Britain and most of Europe.

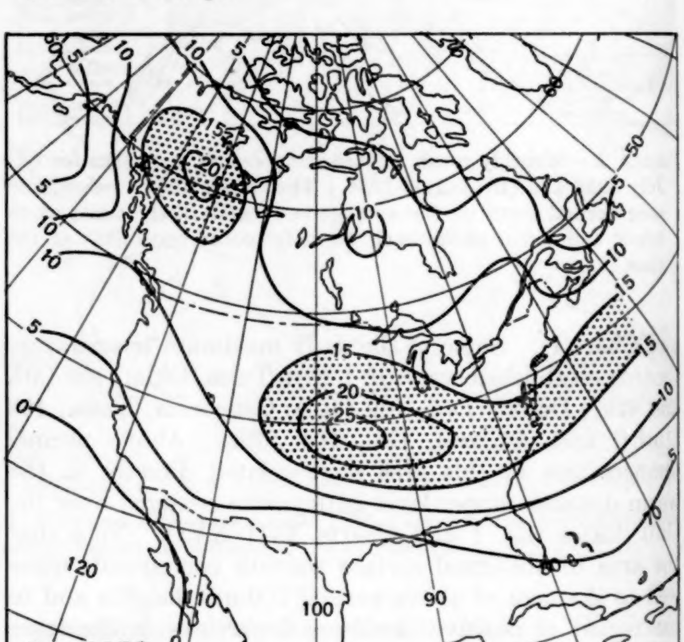



FIGURE 6.—Number of days in August 1956 with surface fronts of any type (within squares with sides of approximately 500 miles). Frontal positions taken from *Daily Weather Map,* 1:30 p. m. EST. Cool, showery weather prevailed quite generally north of the belt of maximum frontal frequency.

This broad belt of precipitation may be related directly to the 700-mb. circulation pattern (fig. 1). Principal contributing factors were confluence and strong cyclonic curvature to the rear of the mean trough over eastern North America. At sea level, the daily cyclones associated with much of this precipitation followed a path from the Northern Plains through the Great Lakes, thence northeastward (Chart X). Most of this precipitation was in the form of showers and thundershowers and fell to the north of the zone of highest daily frontal frequency (fig. 6). In Kansas and Missouri sea level fronts were

present as much as 80 percent of the time, and sea level pressures averaged 3 mb. below normal for the month (Chart XI, inset). Rainfall in the Northwest can be attributed largely to two upper-level cyclones, one at the beginning of the month [4], the other during the last week. These occurred as the west coast trough built northward into the westerlies in response to temporary fluctuations of the long-wave pattern over the Pacific.

Most of the southern half of the country received considerably less than the normal amount of precipitation expected during August (fig. 3B and Charts II, III). The area around Columbus, Ga, suffered its driest August since 1882, while the year just ended at Prescott, Ariz., was the driest of any similar calendar period since 1876–77. Lack of moisture was the principal weather feature during the month in parts of the Central and Southern Plains States, where drought conditions had become quite serious at month's end. This pattern of hot dry weather continued the trend of recent years.

These widespread dry conditions were associated with the extensive upper level anticyclone (fig. 1 and Charts XIII to XVI). At the 700-mb. level heights were predominantly above normal, the largest anomaly being over northern Mississippi. Anticyclonic curvature and wind shear were responsible for large-scale subsidence, and, combined with a weaker than normal import of Gulf moisture in lower levels (Chart XI, inset), can be related to the precipitation deficiency.

## 3. HURRICANE BETSY AND THE LARGE-SCALE CIRCULATION

One tropical storm developed in the southern portion of the North Atlantic during the month and subsequently reached full hurricane intensity. The relation of this storm, named Betsy, to the large-scale circulation pattern is rather straightforward. This is because the circulation in the area and period affected by the storm was representative of the flow pattern existing during the entire month. This was to be expected because the life history of hurricane Betsy occurred during the middle of the month, a time when the flow pattern is most likely to approximate the monthly mean circulation.

The path followed by Betsy is shown in figure 7, superimposed upon the monthly mean 700-mb. contours (same as fig. 1). First spotted August 9, about 900 miles east of the Leeward Islands, Betsy whirled rapidly west-northwestward in the sub-tropical easterlies. The storm passed directly over Puerto Rico, where much damage was done and several lives were lost. (See Weather Notes, p. 311 of this issue.) Skirting the Bahamas, the hurricane, with winds up to 120 m. p. h., posed an immediate threat to the coastal United States. However, as Betsy escaped from the easterly wind belt it decelerated and began a turn toward the north, thus missing the coast but bringing moderate to heavy rains to southeastern coastal areas. After recurvature, the hurricane moved parallel to the coastline and then was swept rapidly eastward as it

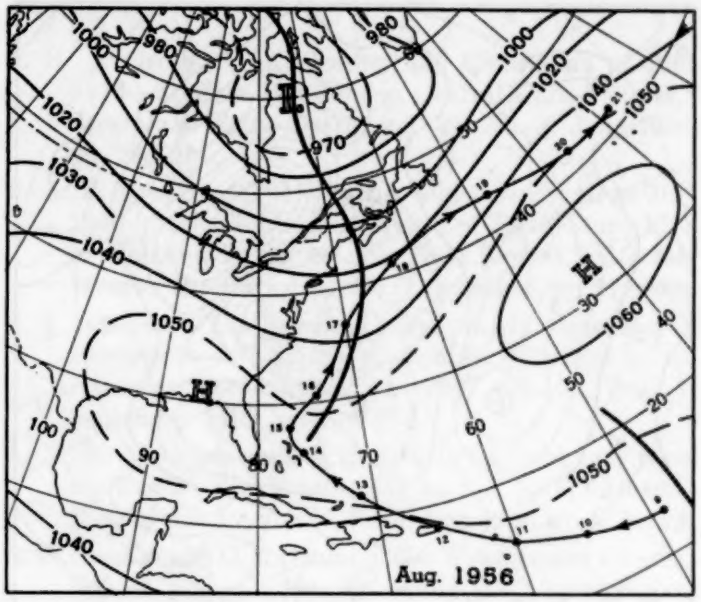



FIGURE 7.—Track of hurricane Betsy, August 9–21, 1956, super imposed on monthly mean 700-mb. contours (same as in fig. 1). Positions given are for 0730 EST. Steering of Betsy by the mean circulation is well indicated.

approached the area of strongest west winds (fig. 4), dissipating in mid-Atlantic on the 21st. In sparing the Atlantic Coast a devastating blow, Betsy did not follow in the path of some of her more famous sisters of recent years.

## 4. CIRCULATION OF AUGUST 1955 AND AUGUST 1956 AS RELATED TO HURRICANE ACTIVITY

During August 1955 [5] hurricanes Connie and Diane, with their flood-producing rains, inflicted much damage upon the northeastern United States. In view of the lack of hurricane activity in this area during August 1956, it was deemed of interest to compare differences in the large-scale planetary circulation patterns for the two months, August 1955 and August 1956. This comparison is, perhaps, best seen in figure 8, which shows the 700-mb. height differences between the two months. There are two very striking features: (1) the widespread and large positive height changes in Polar regions, associated in part with blocking, and (2) the extensive belt of height falls at middle latitudes encircling nearly the entire Northern Hemisphere.

These changes in 700-mb. height were associated with a southward displacement of the hemispheric zonal wind systems from August 1955 to August 1956. That these displacements were quite significant can be seen from figures 4A and 9, where these wind systems are compared. The maximum westerly wind belt (or jet) was displaced equatorward from August 1955 to August 1956 over nearly the whole Northern Hemisphere, with greatest displacement over eastern North America, the Atlantic, and Europe.

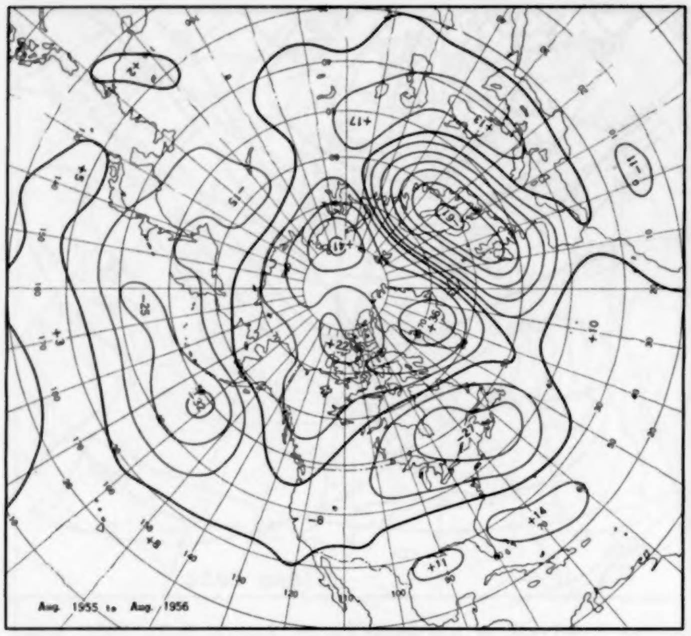



FIGURE 8.—Mean 700-mb. height change (in tens of feet) from August 1955 to August 1956. Areas of large change were associated with marked reversal of the planetary circulation.

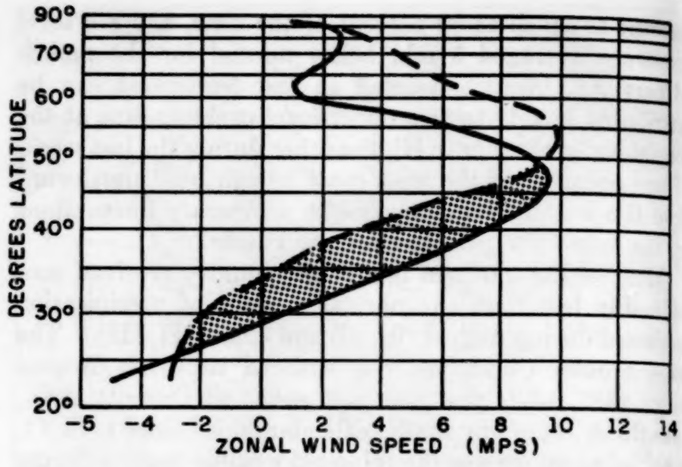



FIGURE 9.—Mean 700-mb. zonal wind speed profiles in the Western Hemisphere for August 1956 (solid line) and August 1955 (dashed line). Note the southward displacement and increase in speed (shaded area) of the hemispheric zonal wind systems from August 1955 to August 1956.

In a recent unpublished study, Ballenzweig [6] has shown that there is a strong tendency for tropical cyclone activity to be at a maximum during years when the mean westerly jet at the 700-mb. level (averaged between 100° and 50° W. long.) is displaced north of normal, and at a minimum when this jet is displaced to the south. The evidence thus far during the early part of the 1956 hurricane season supports this relationship very strongly. Only one tropical storm was observed during August 1956, when the westerlies were south of their normal position, while four tropical cyclones (three full hurricanes) developed in August 1955, when the westerlies were displaced north of normal (fig. 9) [5].

The poleward shift of the westerlies and the axis of the subtropical High over eastern North America in mid-summer 1955 [5, 7] was related directly to the more northward paths taken by hurricanes Connie and Diane before full recurvature. At the same time the weather in the northeastern United States in summer 1955 was abnormally warm with record-breaking rains. These conditions were in decided contrast to the cool, relatively dry regime which prevailed this August (section 2).

An even more pronounced change in circulation occurred over Europe and the eastern Atlantic, where heights at 700 mb. fell sharply, as much as 610 ft., over Scandinavia (fig. 8). This was accompanied by a decided reversal in the circulation pattern, from anticyclonic to cyclonic. At the same time the primary westerly jet axis was displaced southward some 20° of latitude (fig. 4A).

It has been theorized [5] that the strength and north-eastward protrusion of the Azores anticyclone is related to the frequency of occurrence of Cape Verde type storms. If this be true, then the circulation pattern of August 1956 was such as to suppress the genesis of such storms. In this connection the height rises near the Azores (fig. 8) may be indicative of filling of the mean trough which may have spawned hurricane Connie in August 1955.

Thus, it would appear that during August 1956 the large-scale planetary flow pattern was not as favorable for the formation and development of hurricanes as it was during August of 1955. Moreover, the southward displacement of the westerly wind belt in eastern North America greatly diminished the chance of any of these storms striking the north Atlantic Coast.

## 5. WEATHER AND CIRCULATION FEATURES ELSEWHERE IN THE NORTHERN HEMISPHERE

During August 1956 blocking tended to persist in higher latitudes around a large portion of the Northern Hemisphere, although it was somewhat weaker than in July [1]. At the same time the Polar Low was very weak, in sharp contrast to the intense vortex present in July. The principal block was centered over Greenland, where 700-mb. heights were 180 ft. above normal (fig. 1) and sea level pressures as much as 7 mb. above normal (Chart XI, inset). This block effected a displacement of the westerlies south of normal and similarly affected the associated storm track over the eastern Atlantic and Europe.

By far the largest height anomaly was the −360-ft. center (over Scandinavia) associated with the deep trough over western Europe (fig. 1). This anomaly was one of the most extreme negative centers ever to occur during a summer month in the Atlantic or European areas since 1933. It has been exceeded only by the −380-ft. anomaly in the Atlantic in June 1947, and the −370-ft. center over Greenland in July 1955. This abnormally deep center, along with the belt of positive anomaly over North Africa, combined to produce very fast westerlies with a well-

defined jet from the eastern Atlantic to central Asia. Wind speeds were as much as 9 m. p. s. above normal over central Europe (fig. 4B.)

The weather associated with the deep trough and negative anomaly center was unseasonably cool and rainy with much storminess. Cyclonic activity entering Europe from the Atlantic was unusually intense for summer, with sea level pressures averaging from 7 mb. below the August normal in Great Britain to 11 mb. below normal in northwestern Russia. Throughout most of the British Isles there was a considerable deficiency of sunshine, and thunderstorms were unusually frequent. New August precipitation records were established in some districts. Persistent northeasterly flow at sea level swept cool Arctic air masses into Europe, where, in the layer from 700 mb. to 1000 mb., mean virtual temperatures averaged 12° F. below normal (corresponding to a thickness anomaly of −210 ft.) over Great Britain (fig. 5). Note also the strong northeasterly anomalous flow at 700 mb. (fig. 1). This month's cool, rainy regime throughout most of Europe was in sharp contrast to the summer of 1955 when anticyclonic conditions produced warm, dry weather [5, 7].

In the Pacific at least five typhoons were observed in August, with a tendency for these storms to move farther westward before recurving, than is usual for this time of year. Presumably this was related in part to the +90-ft. height anomaly center south of Japan (fig. 1). One of the worst of these storms, typhoon Wanda, smashed into the China coast south of Shanghai early in the month. Two thousand persons were reported killed and millions were made homeless before the storm blew itself out deep in the interior of China.

REFERENCES


1. R. A. Green, "The Weather and Circulation of June 1956—Another Hot June in Central United States," *Monthly Weather Review*, vol. 84, No. 6, June 1956, pp. 236–241.
2. A. F. Krueger, "The Weather and Circulation of July 1956—Including Some Aspects of Momentum Flux in Relation to an Intense Polar Vortex," *Monthly Weather Review*, vol. 84, No. 7, July 1956, pp. 271–276.
3. J. Namias, "The Annual Course of Month-to-Month Persistence in Climatic Anomalies," *Bulletin of the American Meteorological Society*, vol. 33, No. 7, September 1952, pp. 279–285.
4. H. R. McQueen and G. D. Thiel, "A Cold Low Over the Far Western States, August 1–5, 1956," *Monthly Weather Review*, vol. 84, No. 8, Aug. 1956, pp. 313–328.
5. J. Namias and C. R. Dunn, "The Weather and Circulation of August 1955—Including the Climatological Background for Hurricanes Connie and Diane," *Monthly Weather Review*, vol. 83, No. 8, August 1955, pp. 163–170.
6. E. M. Ballenzweig, Seasonal Variations in the Frequency of North Atlantic Tropical Cyclones Related to the General Circulation, unpublished report of U. S. Weather Bureau, Extended Forecast Section, September 1956.
7. J. F. Andrews, "The Weather and Circulation of July 1955—A Prolonged Heat Wave Effected by a Sharp Reversal in Circulation," *Monthly Weather Review*, vol. 83, No. 7, July 1955, pp. 147–153.


# Weather Notes

## BETSY'S ROVING EYE

Between 1700–1900 GMT on August 11, 1956, Hurricane Betsy's eye passed north of the island of Dominica in the northernmost Windward Islands of the Lesser Antilles. After entering the Caribbean Sea the hurricane's eye had a diameter of 10 nautical miles on the Navy reconnaissance aircraft radar as observed by Lt. A. N. Fowler. The eye was continuing what appeared to be a sinusoidal path west-northwestward toward Puerto Rico. (See fig. 1.) The amplitude of its curve averaged about 15 nautical miles and during its initial movement into the Caribbean Sea showed a wave length of 130 nautical miles. From the beginning of its Caribbean trajectory across the Windward Islands until it reached 64° W., the curve crossed its axis on the average of every 5 hours with a period of 10 hours.

At 0400 GMT on August 12, as the eye approached its last well-defined swing to the right, it was 16 nautical miles in diameter with moderate echoes in several spiral bands extending 70 nautical miles north and 40 west. However after it reached 65° W., the track of the eye lost its sinusoidal character. This might be explained by the slight change in direction from west-northwest to northwest. In addition, the storm's proximity to the Virgin Islands and Puerto Rico may have somewhat distorted its rhythmic movement.

Precipitation bands around the circulation eye continued to vary the diameter and at 0830 GMT the center was 18 nautical miles across located about 75 nautical miles to the southeast of Puerto Rico. Somewhere in this location the storm inflicted its first loss of life inside the Caribbean. The *Elena*, a 91-ton vessel en route through the Virgin Islands, broke up so fast that the crew was unable to radio for help and two seamen were drowned. Another larger ship, the 4,381-ton tanker *Michael J.*, was more fortunate. On Saturday morning it heeded the hurricane warnings and when it was south of St. Croix, it began fleeing southward. Several days later it was located 200 miles south of Puerto Rico adrift with engine trouble and without radio contact.

By 0845 GMT the hurricane was located on the San Juan radar but because of local obstructions and terrain to the southeast of the station the eye could not be fixed.* Between 1200 and 1230 GMT a closed circulation was observed with a diameter of 8 to 10 nautical miles. This was one of the smallest diameters so far reported along the track and indicated that precipitation had closed the eye with concentric bands as it neared the land. As it approached the southeastern coastline its movement between 1200 and 1230 GMT oscillated back and forth and was so erratic that it seemed to be deflected by the terrain. (Perhaps an analysis of the radar film will show somewhat less oscillation than is shown in the radar track plotted on figure 1.) The terrain in the southeastern coastal area slopes abruptly from the coastline to about 1,500 feet with a peak of 2,890 feet in the Sierra de Cayey chain. The eye entered the coastline near Maunabo and moved near Yabucoa, then curved erratically westward toward Guayama. Calm winds were reported at Maunabo as well as at Patillas indicating the eye's passage through these towns.

It is difficult to believe that hurricane Betsy could be deflected by terrain of such dimensions. If the radar positions of the eye were eliminated between 1200 and 1230 GMT, the extrapolated track from the southeastern coast of Puerto Rico to the northwestern coast would assume a more symmetrical line and would even tend toward a quasi-sine curve. Unfortunately there were no pressure readings while the hurricane was in this area. The eye was distorted and seemed to be breaking up over land at 1300 GMT. At 1315 GMT the eye was in the vicinity of Cayey and calm winds were reported there, At that time the eye's diameter was around 6 nautical miles with a sharp tilt toward the northwest. Cayey is located in a valley in the Central Cordillera bounded by peaks of 2,500 to 3,000 feet on the east and 2,200 to 2,800 feet on the west. At one time the eye was observed to take a "square" shape on the scope. Mr. Rockney momentarily fixed the radar antenna at 5,000 feet and the eye was observed to take a more circular shape.

*The radar observer during this period was Mr. Vaughn Rockney.

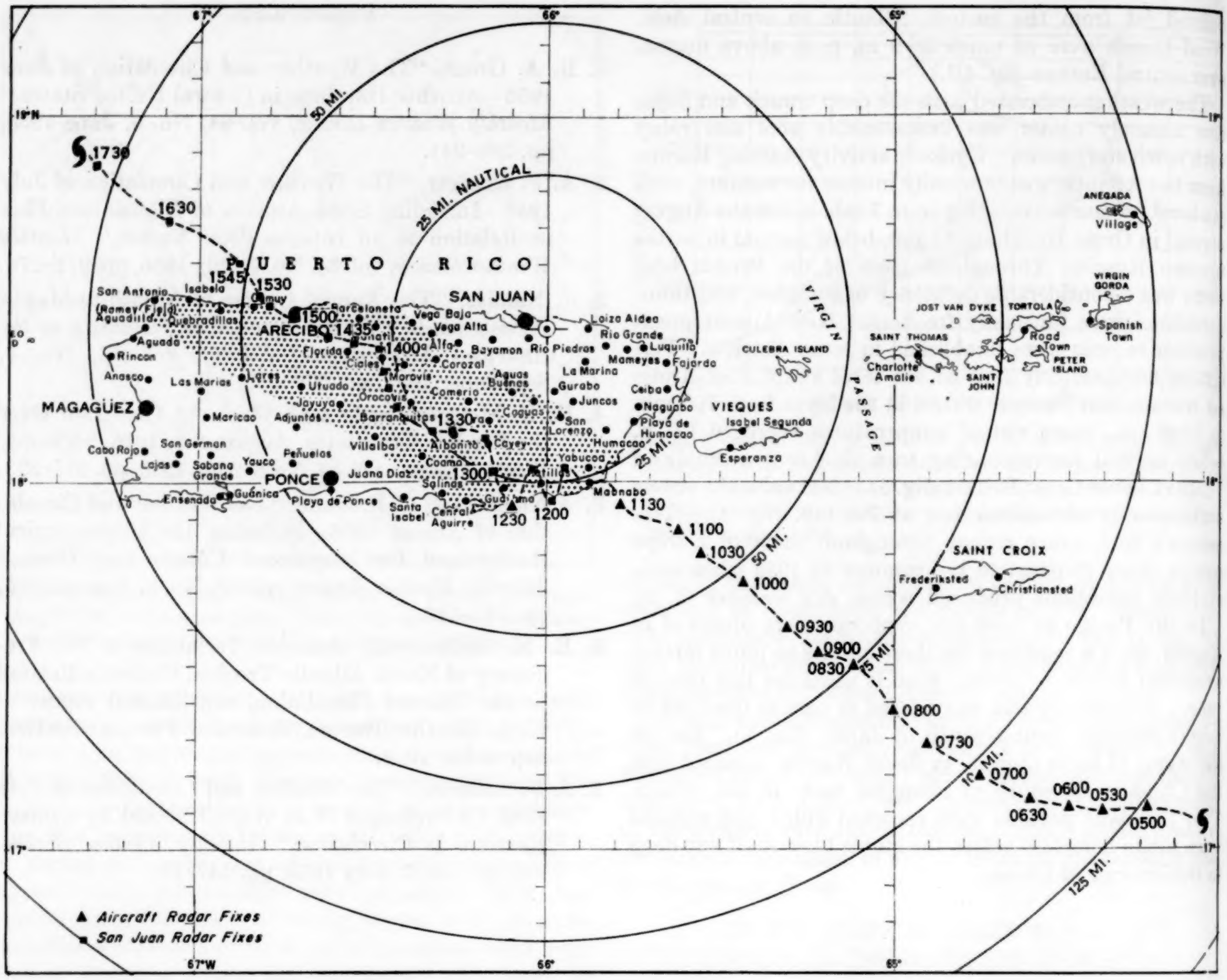



FIGURE 1.—Radar track of hurricane Betsy across the island of Puerto Rico, August 12, 1956. Plotted numbers give time of radar fixes in Greenwich Mean Time. Stippled area is path of greatest damage.

Tilting of the antenna showed that the upper and lower positions of the eye did not coincide as the lower part was being held back by the friction of the terrain.

The movement of the eye from Cayey to Aibonito through the Central Cordillera was west-northwestward and caused considerable damage. An eye witness account of the valleys in the area southwest of Cayey reports that the lower valleys were practically denuded of trees while trees on the ridges were relatively intact. This phenomenon might be explained by the funnelling effect of high winds. Aibonito reported calm winds with the passage of the eye. This town is about 2,000 feet above sea level with peaks of 2,400 feet to the immediate south and 2,780 feet 10 miles to the west. The high winds at Aibonito resulted in more than 1,000 homes being destroyed and 500 partially demolished. The movement of the eye northwestward from Aibonito to west of Orocovis is over some of the highest terrain along the track. In this area peaks range from 3,127 feet to the east of track to as high as 3,442 feet to the west of track. Between 1330 and 1400 GMT calm winds were reported at Barranquitas, Orocovis, and Ciales. At Comerio, a small town in the Cordillera just east of the eye's path, 579 houses were totally destroyed and 706 were in uninhabitable condition.

The terrain from the Central Cordillera to east of Camuy where the eye left Puerto Rico is gradually downslope with minor hills near the coast. Calm winds were reported at Florida, Arecibo, and Camuy between 1400 and 1530 GMT. There seems to have been a slight acceleration of Betsy after it crossed the Cordillera and by 1545 GMT the hurricane had intensified off the coast north of Camuy with the diameter of the eye now larger over water at 25 nautical miles. Ramey Field on the extreme northwestern coast of the island reported wind gusts of 115 m. p. h. between 1606 and 1612 GMT. The lowest pressure observed over Puerto Rico was at Ramey Field, 28.88 in. This compared to 29.02 in. at San Juan International Airport and 29.56 at the San Juan Naval Station.

It was estimated that the path of greatest damage extended about 20 miles north of the track and a little less to the south. A preliminary report furnished by Civil Defense showed that the two towns nearest the eye's point of entry, Maunabo and Yabucoa, were the hardest hit. Between 12,000 and 15,000 people were reported homeless at Yabucoa alone, with $8 million worth of agricultural and property damage. Betsy's roving eye was estimated to have cost Puerto Rico $25 million in overall damage. The hurricane caused severe damage to all crops in the Jayuya area: bananas were a 100 percent loss, and the coffee crop will take several years to recover. At Camuy, the eye's track dealt its last effective blow to crops—100 percent of the corn, 95 percent of the avocado, 65 percent of the breadfruit and 50 percent of the coffee crop ruined.

In spite of these heavy property and agricultural losses, it is amazing that the total death toll was only 9. The small casualty list is indicative of the large number of people who heeded the warnings and took cover in Civil Defense shelters.—*Robert J. Grace, WBAS, San Juan, Puerto Rico.*

# A COLD LOW OVER THE FAR WESTERN STATES, AUGUST 1-5, 1956

H. R. McQUEEN AND G. D. THIEL

National Weather Analysis Center, U. S. Weather Bureau, Washington, D. C.

## 1. INTRODUCTION

The northeastern portion of the North Pacific Ocean and its adjacent land areas is a well known source region for the cold-type Low. Although, not unique in this type of cyclonic perturbation, this locality is one of the most prolific sources of cold Lows that affect the United States. The area of maximum occurrence tends to migrate northward along the west coast of North America during the summer months and southward in the winter. Cold Lows or "cold pools", as they are referred to by the British, have been rather well defined by Sumner [1] ". . . a mass of cold air in depth entirely surrounded by relatively warm air and appears as one or more closed lines in the thickness isopleths for any fairly deep atmospheric layer."

This article discusses the formation of a cold Low and indicates certain points that might aid in forecasting similar developments in the future. A summarization of the weather in essentially a qualitative manner is presented, as well as a few ideas that may aid in the forecasting of stability or instability and of temperature maxima or minima.

## 2. ANTECEDENT CONDITIONS

The well-developed subtropical anticyclone which persisted over the North Pacific Ocean during the period of interest, August 1-5, 1956, was also present for some time prior to and following this period. This High or an associated High apparently had its inception around July 15, 1956 with its center originally located from 10° to 15° of longitude east of the International Date Line. Downstream from this position a long-wave trough was established over the eastern portion of the Pacific. Coexistent with this trough and the ridge was an upstream long-wave trough over eastern Siberia; this latter trough remained practically stationary with regard to any east-west motion and was rather weak throughout most of the 3-week period, July 15-August 5.

By the 20th of July, an eastward-building ridge, extending toward the California and Mexico coasts, had developed in the southern portion of this Pacific anticyclone. Concurrently in the upper air the continental High over southeastern United States was building westward, finally coalescing with the Pacific ridge, and with this merger a new High began to appear between 145° and 155° W. Because of this development there began a redistribution in the wavelength and pressure center patterns over the Pacific Ocean and North America. The long-wave trough off the west coast weakened and moved eastward over central North America, while the long-wave ridge just east of the Date Line moved westward to near 170° E. and, for the most part, south of the 45th parallel. The Siberian long-wave trough continued in much the same position as previously, north and west of the ridge.

During the next few days a pronounced block formed, extending from the central Pacific Ocean northeastward to the vicinity of Great Bear Lake, Canada, and thence eastward across the Davis Strait and into the eastern Atlantic. By July 25 the westernmost Pacific High was weakening and merging with the high cell centered at 40° N., 145° W. The Siberian long-wave trough had intensified, and this was to play an important part in future downstream developments through the dispersion of energy. The block, which then extended from the mid-Pacific area to Alaska and thence across northern Canada, had intensified during the past day or two. This intensification increased the downstream transport of cold Arctic air west-southwestward into southern Canada thus producing and developing a trough from Hudson Bay to British Columbia. The chart (not shown) of the 700-mb. 5-day mean height departure from normal for the 5-day period centered on July 26 indicated the following positive anomaly center values: 420 ft. at 50° N., 165° W; 450 ft. approximately 330 miles north of Great Bear Lake; and 370 ft. midway between Labrador and southern Greenland. Negative anomaly center values were 190 ft. near Wrangel Island, 200 ft. at the North Pole, and 230 ft. over southern Hudson Bay. The Hovmöller Chart [2] in figure 1 shows that also on this date, July 26, the 500-mb. trough associated with the Siberian Low reached its maximum intensity.

Between July 26 and 28, 1956, both at the surface and aloft, the anticyclone over the Pacific retrograded with its central position becoming nearly stationary at 50° N. and 165°-170° W. During this regression a series of surface waves and attendant short-wave troughs caught in a strong meridional flow around the western periphery of the large Pacific anticyclone moved northward toward the

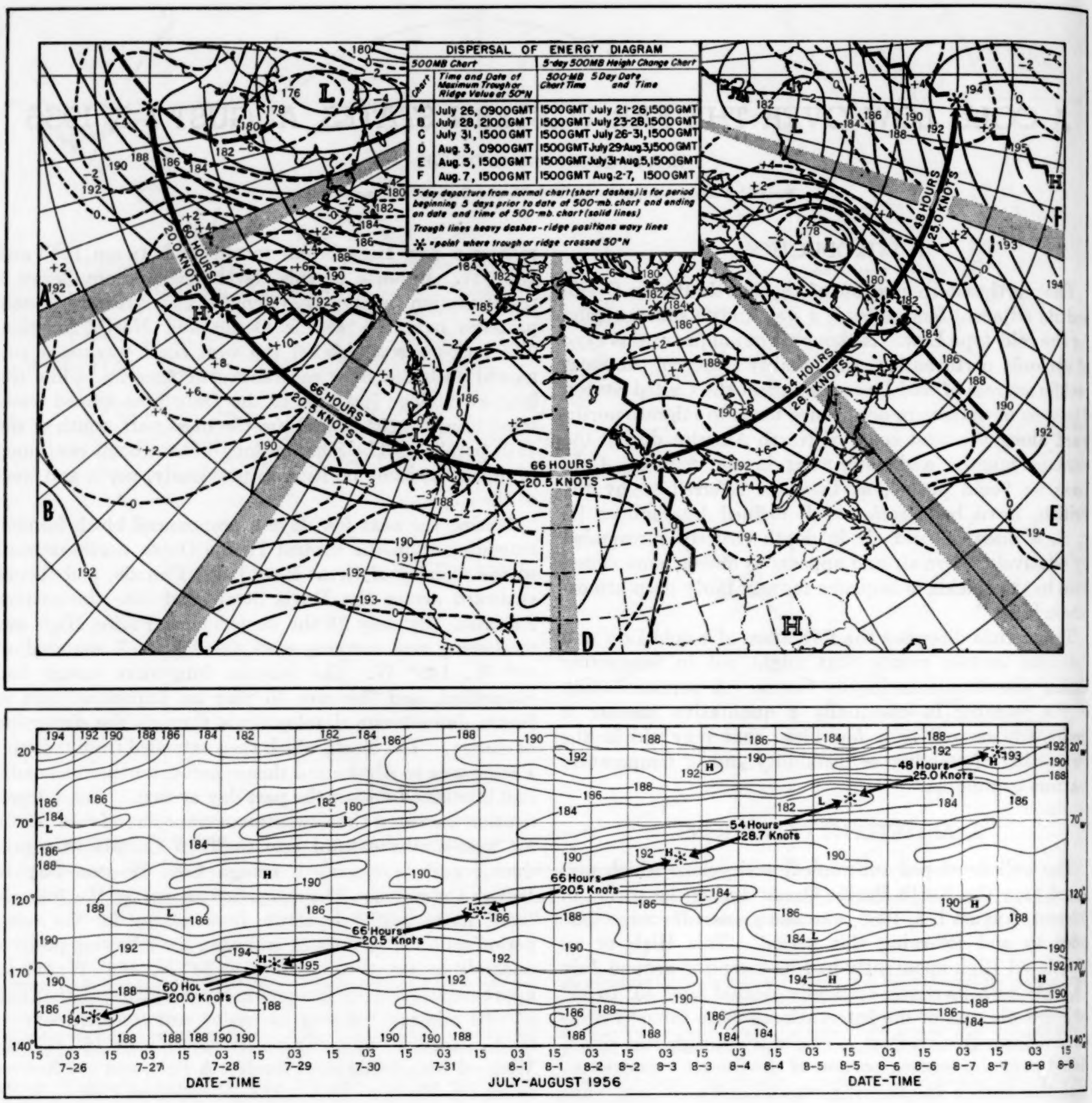



**Figure 1**—Upper—Composite 500-mb. chart in six sectors illustrating the period and time of maximum intensity of troughs and ridges as a result of downstream dispersion of energy at 50° N. Lat. Heights are in hundreds of feet. Dashed lines represent the 5-day change of 500-mb. height for the period immediately prior to the time of the 500-mb. chart. Positions at maximum intensity are clearly marked by heavy dashed lines for troughs and heavy zig-zag lines for ridges. Speed of dispersion and time in hours between periods of amplification are placed between arrows. Lower—Hovmöller diagram presenting a time-longitude cross section of the 500-mb. height at 50° N., extending from 150° E. eastward to 5° W. during the period 1500 GMT, July 25, 1956 to 1500 GMT, August 8, 1956. The heavy black line connecting alternate ridge and trough centers represents the trajectory of the dispersion of energy downstream the same as indicated on the upper chart by the arrows along the 50° N. parallel. Heights are in hundreds of feet. The H and L do not normally locate the center of an anticyclone or cyclone but merely indicate the highest or lowest value attained in ridges or troughs at 50° N.

region of the Pole. As these waves moved into the region of the cyclonic vortex there occurred a continued lowering of the central height value in the long-wave trough which originally had been located near Wrangel Island but was then being carried northward toward the Pole. Also occurring during the recession of the Pacific High center was the re-establishment of the eastern Pacific trough. This was occasioned by the depression over southern Canada building westward across the southwestern Provinces and thence southward along the Pacific Coastal States. By July 29 this southward extension of the eastern Pacific trough had severed the east-west ridge joining the Pacific and the continental Highs.

The Siberian Low, by July 29, had assumed a more circular appearance and had intensified with the central value of the 5-day mean 700-mb. height departure from normal having lowered 300 ft. since July 26. During this same period the central value of the Pacific High had risen 100 ft. in height. This isallobaric intensification and the weakening of the long-wave trough to the northwest of the High produced a westward displacement of the ridge line. Thus, there was established a strong isallobaric gradient between these two pressure systems that attained a value of 600 ft. between 65° N. and 75° N. on the chart of 5-day mean 700-mb. height departure from normal. A similar but more intense pressure gradient was indicated by the daily 700-mb. and 500-mb. charts with air flow becoming more zonal than meridional from north central Siberia into Alaska and the Yukon. Under this air flow cold Arctic air was rapidly transported into Alaska and the Yukon, gradually but definitely weakening the persistent ridge that had prevailed for some time across Alaska and northern Canada. Also, recurrent short waves, attending surface waves which were moving downstream in this westerly flow, continued to erode the ridge, and by the 31st of July a zonal flow had been established across northern sections of British Columbia and Alberta. Concurrent with this development was the formation of a cut-off cold Low with a central height of 18,500 ft. at 500 mb. near Port Hardy, Vancouver Island, B. C. Graham [3] found in his studies covering the years 1947–52 that this locality was most prolific of cyclones during the summer season reaching a percentage frequency of 2.2 for the occurrence of cyclones at 500 mb. per 100,000 km.$^2$. This value, by the way, was the highest noted for any season of the year within the area from the west coast of North America to 145° W. and from 25° N. to 55° N. Furthermore, in this instance the downstream dispersion of energy was approaching its maximum intensity along the 50th parallel between 125° and 130° W., furnishing additional support for the development of the closed Low. The long-wave trough, within which this cold Low was enclosed, extended southwestward from Port Hardy, Vancouver Island to southeast of Johnston Island.

## 3. DEVELOPMENT OF THE COLD LOW

The development of the cold Low near Port Hardy at the end of July 1956 occurred during a seclusion process in the upper air. Originally the Low was a portion of a cold trough that had formed on the downstream side of a pronounced high-latitude block which extended from the mid-Pacific northward and eastward along the southern limits of the Arctic Circle. The trough in this particular case had a southwest-northeast orientation and reached from central Canada to southern British Columbia and thence into the Pacific. A jet stream was located along the western periphery of the Pacific ridge and in the levels beneath the jet warm air was being transported northward and eastward. But with the tightening of the gradient along the northern portion of the ridge and the steepening of the thermal gradient between the Low centered north of Wrangel Island and the Pacific High center, a resultant acceleration in the speed of the jet stream occurred. Thus, by July 29–30, as the jet stream recurved southeastward around the northern portion of the Pacific ridge, the increased eastward momentum resulted in the transporting of warmer air slowly across height lines. Gradually, due to this eastward transport of warm air and also to subsidence as indicated by negative vertical motion values on the Joint Numerical Weather Prediction charts (not shown), there occurred a seclusion of the cold trough. This pattern of formation of the cold Low followed much the same development as presented by Palmén and Nagler [4] who stated: "Thus the polar air in the cyclonic area to the south was completely secluded from its original source region . . ." And in the same manner by July 31, 1956, the cyclonic system that is the cold Low studied in this article had been born.

## 4. SYNOPTIC CONDITIONS, AUGUST 1–5

The surface and upper air charts for August 1, at 1230 and 1500 GMT respectively (fig. 2) indicated a definite southward movement of the cold Low, which on the previous day had formed near Port Hardy, B. C., to near Astoria, Oreg. Considerable intensification had occurred during the past 24 hours with the innermost closed height line at 500 mb. being 18,400 ft. This height value represented a negative departure in excess of 500 ft. from the normal 500-mb. height at the anomaly center and a change of −400 ft. during the past day. It is difficult to associate this cut-off Low with any of the surface depressions other than possibly the weak cyclonic center near Yakima, Wash. During the past day the 1000–500-mb. thickness packing northwest of the stationary surface Low near Boise, Idaho, had intensified considerably. Because of this it became necessary to extend the stationary front southwest of Boise and to change its classification to a cold front of strong intensity. That cold air was moving southeastward was

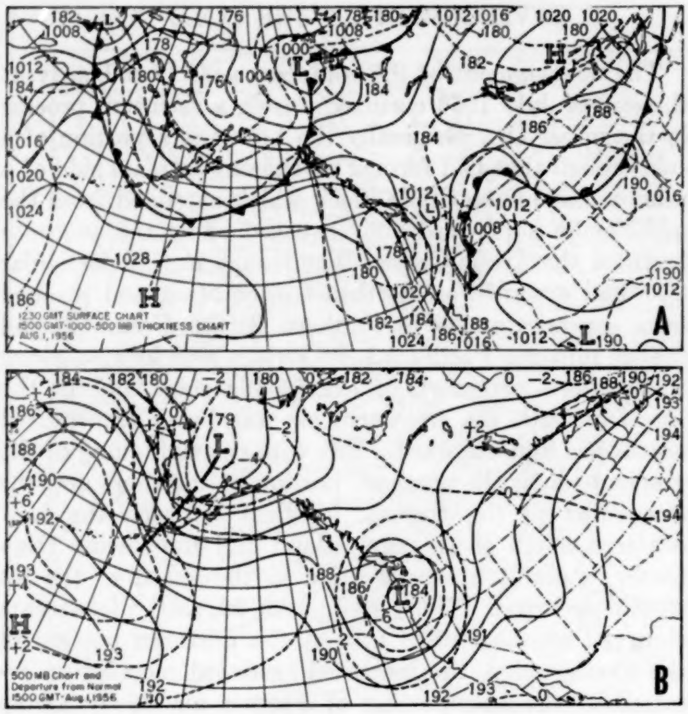


FIGURE 2.—Synoptic patterns for August 1, 1956. (A) 1230 GMT surface chart (solid lines) with 1000-500-mb. thickness for 1500 GMT (dashed lines). Surface reflection from upper cold Low appears extremely weak over eastern Washington State while intensity of gradient of thickness over western Oregon clearly defines pool of extremely cold air. (B) 1500 GMT 500-mb. chart shown by solid lines. Departures from the normal 500-mb. height for August are shown by dashed lines. Strong isallobaric departure from normal height is practically symmetrical with cold Low.

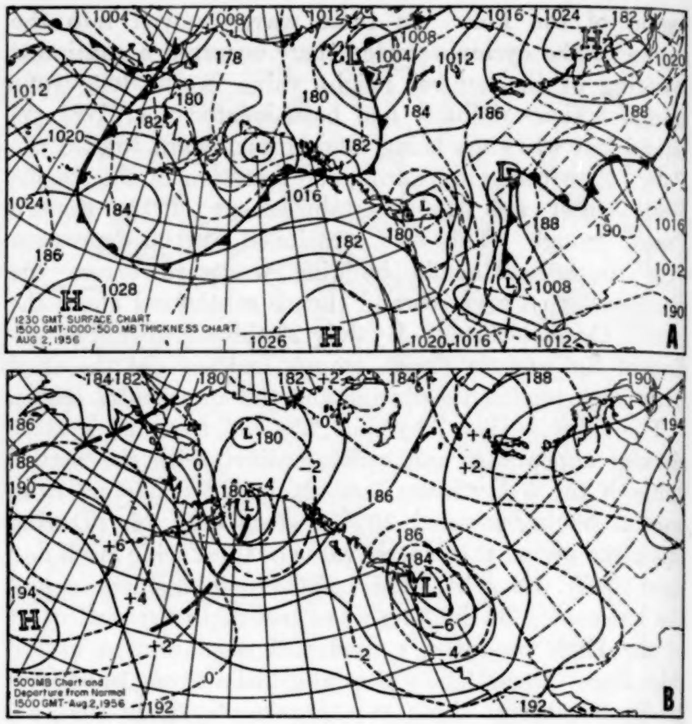


FIGURE 3.—Synoptic patterns for August 2, 1956. (A) 1230 GMT surface chart (solid lines) with 1000-500-mb. thickness for 1500 GMT (dashed lines). Surface reflection from upper cold low continues weak; little change in thermal gradient. (B) 1500 GMT 500-mb. chart shown by solid lines. Departures from normal 500-mb. height for August are shown by dashed lines. Low center practically stationary with no change in intensity.

borne out by the 24-hour thickness change chart which indicated height falls of 500 or 600 ft. at Medford and Salem, Oreg. As the mean temperature of the 1000–500-mb. layer approximates the 700-mb. thermal field, this change depicts temperature changes between 7° and 9° C. at those two stations in the past day.

In the north central and northwestern corner of figure 2A, there may be observed two of the minor waves that were moving about the intense Low north of Siberia. The Low near Great Bear Lake, Canada, although relatively weak as was the attendant cold front, was associated with a well-developed trough upstream at 500 mb. and an area of maximum cyclonic vorticity.

These two Lows, one near Great Bear Lake and the other the cold Low, produced a rather well-formed col or deformation field over British Columbia, Alberta, and Saskatchewan, Canada. From streamline flow it appeared that, in general, this could be classed as deformation with negative rotation except for slight asymmetry in the shape of the hyperbolas due to slight divergence. Thus, this would be a case in which negative vorticity was present and so any cyclone that might be approaching this col area would tend to slow down. The pair of high pressure cells that were associated with this col were the two persistent long-wave ridges that had been over the central or eastern sections of the United States and the old mid-Pacific subtropical anticyclone. A casual glance at the 500-mb. height departures from normal clearly illustrates the current intensity of the Pacific anticyclone with heights in the Bering Sea locally in excess of 600 ft. above normal, while over the central portion of the United States heights in the ridge were only slightly above the monthly average.

The warmth of the upper air in the Bering Sea and northern Canada is shown quite well on the 1000–500-mb. thickness charts by the 18,400 ft. thickness line being far to the north of its normal position and by the 500-mb. and 700-mb. temperatures which were 5° to 7° C. above normal for these regions. On the other hand, temperatures in the central portions of the cold pools, as delineated by the low thickness values over Oregon and Alaska, were indicated by the departures from normal thickness (not shown) for these areas to be below the normal for August by 6° to 9° C. at 700 mb. and by 5° to 7° C. at 500 mb. The areas of maximum 24-hour 500-mb. height rises or falls during the past day were quite well aligned with the ridges and troughs. These height changes showed the ridges had built to the north and east, while

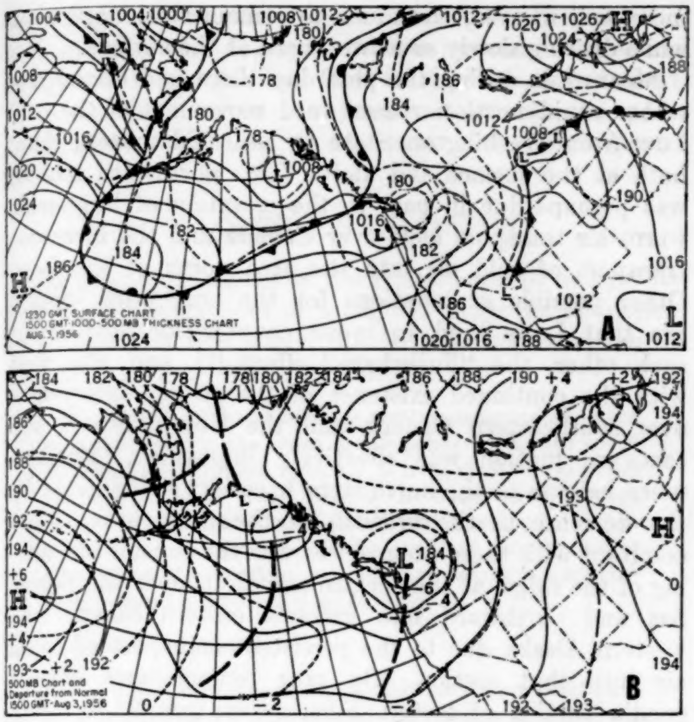


Figure 4.—Synoptic patterns for August 3, 1956. (A) 1230 GMT surface chart (solid lines) with 1000-500-mb. thickness for 1500 GMT (dashed lines). (B) 1500 GMT 500-mb. chart shown in solid lines with departures from normal 500-mb. height for August in dashed lines. Continued southward weakening of height values over eastern Pacific clearly indicated.

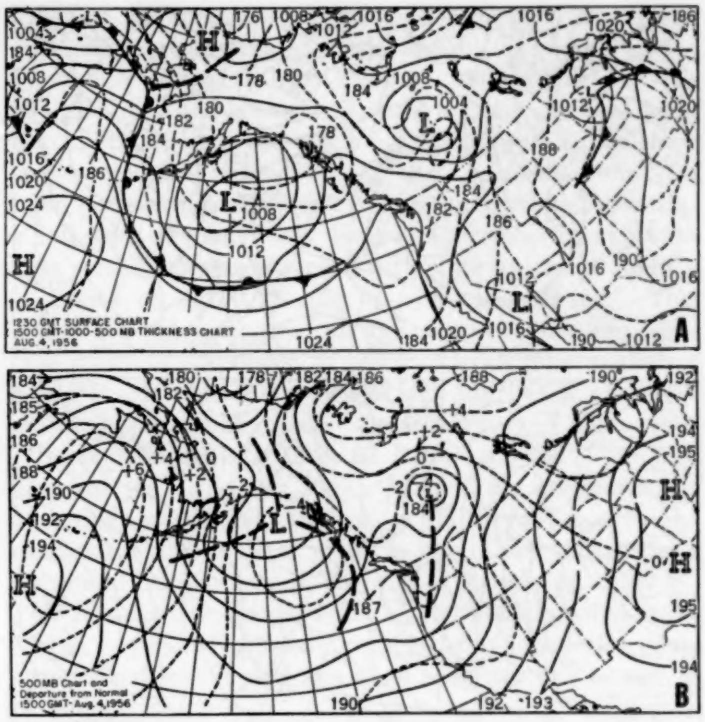


Figure 5.—Synoptic patterns for August 4, 1956. (A) 1230 GMT surface chart (solid lines) with 1000-500-mb. thickness for 1500 GMT (dashed lines). (B) 1500 GMT 500-mb. chart (solid lines) with departures from normal height for August in dashed lines. Building of ridge northward toward Alaska is plainly visible.

the troughs had deepened to the south and southeast. Height rises of 400 ft. had occurred in the northern Bering Sea and western Hudson Bay, while falls of similar magnitude were near the negative anomaly centers on the 500-mb. chart.

On August 2, 1956 the 1200 GMT surface and the 1500 GMT 500-mb. charts (fig. 3), indicated only minor changes in the intensity of pressure centers and in the position of the ridges or high centers, and nearly normal movements of fronts and troughs. The few changes may be sketched briefly. The cut-off Low moved inland over Washington State where it was centered near Yakima. A new cyclonic development appeared south of Anchorage, Alaska as the area of maximum vorticity moved into that region and a minor wave formed south of the cyclonic development. The large Pacific High which previously had encompassed most of the North Pacific had developed a second center about midway between Hawaii and the Puget Sound region. South and southwesterly winds about the western portion of these anticyclones had continued to transport warm air northward and eastward of the high center, thus permitting a continued building of the ridges. This was most pronounced over central Canada where the chart of the 500-mb. height departure from normal showed a 400-ft. positive anomaly, an increase of 200 to 300 ft. from the preceding day. Most other anomaly values of height and thickness were relatively constant even though another minor trough had appeared over eastern Siberia on the 500-mb. chart. The area of deformation with negative rotation continued to be maintained over southwestern Canada.

By August 3 the surface center of the cold Low (fig. 4A) was still poorly defined. At 500 mb. (fig. 4B) the area enclosed by the 18,400-ft. height line had increased as a trough developed between this center and the Gulf of Alaska Low. Thickness changes during the past day indicated slight modification of the temperatures associated with the cold Low over Washington State as well as a slight drift of the cold air to the north-northeast. Over the eastern Pacific the gradual weakening of the high cell, both surface and aloft, continued as cooler air was transported southward to the east of Hawaii. However, concomitantly with this weakening, the ridges over the Bering Sea and central Canada continued unchanged or built slightly. This building was most pronounced in the Canadian region for it was about this time that the eastward progression of amplitude increases in troughs and ridges reached a maximum in the ridge at 50° N., 95° W. (fig. 1). Over Siberia continued advection of warm air northeastward toward Alaska was indicated, with eastern Siberia reporting 700-mb. temperatures as much as 9° C. above normal. Minor waves continued to move southward and eastward along the western periphery of the long-wave trough that extended from the States of Wash-

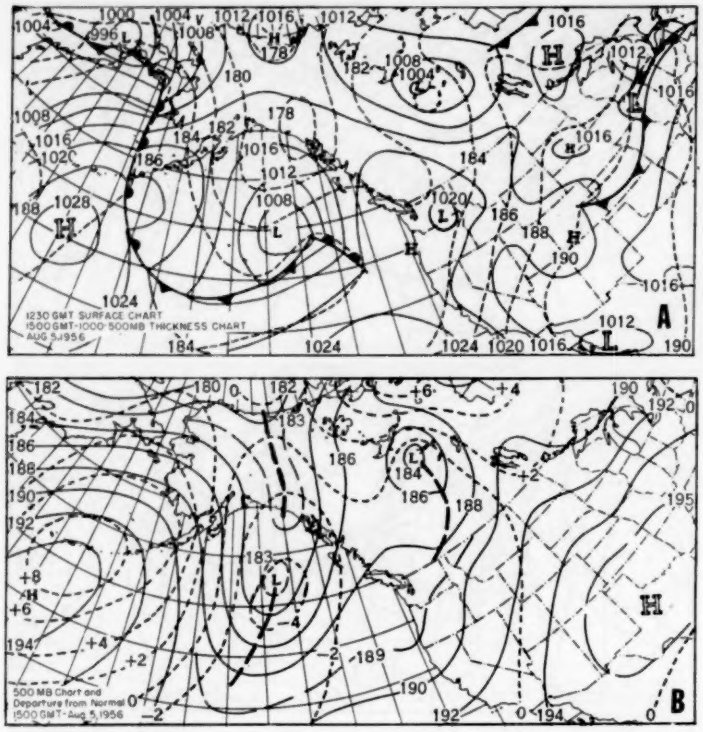



FIGURE 6.—Synoptic patterns for August 5, 1956. (A) 1230 GMT surface chart (solid lines) with 1000-500-mb. thickness for 1500 GMT (dashed lines). Thickness packing about cold Low practically dissipated as Low moved northward to more comparable temperature values. (B) 1500 GMT 500-mb. chart (solid lines) with departures from normal height for August in dashed lines. Weakening of trough over Alaska indicated as ridges continue to strengthen.

ington and Oregon northwestward to the intense cyclone centered north of the Bering Strait. The col at this time appeared to be assuming a more neutral character or, after Petterssen [5, 6], the hyperbolic streamlines tended to indicate a region of nearly pure deformation or an area without vorticity.

The surface and upper air charts for 1230 and 1500 GMT of August 4, (fig. 5) indicated, for the first time, a well formed and developed surface center in conjunction with the cold Low. The col had assumed a deformation pattern with positive rotation or cyclonic vorticity. In line with Petterssen's [5] statement that "Cols of cyclonic vorticity represent a potential cyclogenesis," it is believed that this cyclonic vorticity was as least partially responsible for the intensification of the surface Low. Along with the surface intensification there continued a slow modification of the low temperatures aloft and slight weakening of the upper centers. Temperatures at 700 mb. were from 3° to 5°. C. lower than normal in the region of the cold Low and attendant trough.

Continued slow southward transport of cool air had been maintained over the Pacific from Hawaii to the mainland with a resultant gradual decrease in heights over that region. The Gulf of Alaska cold Low, although increasing in area, continued to remain stationary aloft while drifting slowly southwestward at the surface.

Meanwhile during the past day there had occurred a rather rapid north-northeastward movement of the cold Low from Washington State to near Edmonton, Alta. both at the surface and aloft. This northward motion was perhaps due in part to the cessation of large-scale warm air transport aloft over Canada and the increased transport of cold air into the area north of the Low. Other possible explanations for the northward motion are that Lows tend to move counter-clockwise about each other, the "Fujiwhara" effect [7], and also that with the continued existence of the strong anticyclone over southeastern Canada and the United States any eastward motion was effectively impossible. Furthermore, heights to the north were lowering, as indicated by the decrease in the breadth of the ridge area. Concomitant with these occurrences was the continued building of the ridge, at the surface and aloft, over the Bering Sea and northward into extreme eastern Siberia and western Alaska due to the persistent transport of warm air into that section. By now temperatures over a goodly portion of eastern Siberia were from 9° to 11° C. above normal at 700 mb. as indicated by the 1000–500-mb. thickness departure from normal. Ahead of this building ridge was observed a short-wave trough with an intensifying zone of cylconic vorticity which was moving southeastward into a weak frontal region. Meanwhile the short-wave trough approaching the west coast had weakened considerably during the past 24 hours.

By August 5, 1956 (fig. 6) the effect of the cold Low over the Northwestern States was diminishing rapidly, but a rather persistent trough remained across the States of Washington and Oregon while the Low moved nearly northward to Fort Smith, Alta. Little change occurred insofar as the intensity of the actual 500-mb. height value was concerned but the packing of the 1000–500-mb. thickness diminished as temperatures at 700 mb. and 500 mb. returned to near normal. This change indicated a tendency for the Low to weaken henceforth, since its northward movement had removed the thermal field discontinuity, leaving it associated with air of almost uniform temperature. At the same time the trough across eastern Alaska had weakened and the upper-air height values had returned to near normal to the west of Aklavik, Canada. Over the Pacific the High began to intensify and to increase in size as a strong zonal flow along its northern periphery began noticeably to transport warmer air well into Alaska and the western part of the Gulf of Alaska. The cold Low previously in the Gulf was now nearing ship "Papa" (50° N., 145° W.) with slight weakening of the central value, but intensification had occurred in the trough that extended southward. However, this change was short-lived as during the next two days continued eastward transport of warm

air dissipated the cold trough over the Gulf of Alaska, and by the 8th of August above normal heights had bridged from the Alaskan Gulf to the Washington coast. With this change in the pressure pattern, the polar troughs were deflected to the east of the Continental Divide.

## 5. DISPERSION OF ENERGY

Before the discussion of the relationship of energy dispersion to occurrences of trough or ridge amplification, as analyzed in this study, a brief review of this subject may be in order. Rossby [8] states:

> Practically all forms of wave motion encountered in the atmosphere or in the ocean are dispersive, i. e., the speed of propagation (phase velocity) of individual waves is dependent on their wave length. In such wave systems energy is propagated at a speed which normally differs from the phase velocity. If the speed of propagation of energy exceeds the phase velocity, new waves will be generated ahead of the initial wave train.

Later Carlin [9] stated,

> If two sets of waves of slightly different wave length are traveling through a medium and the velocity of the waves (phase velocity) is a function of the wave length, then one of the sets of waves will travel faster than the other . . . The velocity of the regions of reenforcement or interference is called the *group velocity* . . . The increase and subsequent decrease in wave amplitude is often observed to travel along a wave train at a rate much greater than the phase velocity of the wave, and it is this phenomenon which is believed to be directly associated with group velocity.

And more recently Petterssen [6] gave a very lucid discussion of the subject. He states that the group velocity, or the downstream speed of the envelope wave is greater than the zonal wind speed, and that the speed of downstream propagation of the amplification of the individual troughs and ridges gives the magnitude of the group velocity. The speed and intensity of the amplification is well illustrated by and usually extrapolated from a Hovmöller [2] diagram. Petterssen further points out that the very long waves, when identified by either space smoothing (e. g., as by the space mean chart) or by time smoothing (e. g., the 5-day mean chart as used by the Extended Forecast Section), usually remain nearly stationary for rather long periods, while the individual troughs and wedges advance through the long-wave trend at an approximate speed of 10° long. per day; on the other hand, the group velocity or amplification of the individual troughs and ridges has a downstream propagation speed of approximately 30° long. per day.

As has previously been mentioned, one of the contributory factors in the intensification of the trough over southwestern Canada and the eastern Pacific and the subsequent development of the cold Low over British Columbia is believed to have been the dispersion of energy downstream in the mid-tropospheric long-wave pattern. This amplification of the individual troughs and ridges was found to have propagated downstream with a group velocity of the order of 20 knots during the past 5 days. The initial appearance of an area of reinforcement was noted on the Hovmöller diagram (fig. 1–lower) at latitude 50° N., 164° E. upon the intensification of a trough at that location. The 24-hour 500-mb. height changes failed to show any conclusive indications of that intensification, but upon preparation of a 5-day 500-mb. height-change chart, a fall area of moderately large proportions for summertime conditions was observed with a central value slightly in excess of −700 ft. (fig. 1–upper, sector A). This maximum value occurred on July 26, at 0900 GMT. In a case study of dispersion of energy Carlin [9] stated that 5-day charts were more satisfactory than daily charts in indicating height changes and planetary movement.

Some 60 hours later (July 28, 2100 GMT) the Hovmöller diagram (fig. 1–lower) indicated definite intensification of a ridge at 50° N., 165° W. with the 500-mb. height change for the 5 days prior to this time indicating a maximum reinforcement slightly in excess of 1,000 ft. This downstream propagation of amplification had traveled at a speed of approximately 20 knots, while the computed zonal wind speed was 5° of long. per day or nearly 14 knots.

The next stage of trough amplification occurred along the west coast of North America at 50° N., 130° W. in association with the cold Low development (fig. 1–upper, sector C). In this region the picture of true deepening was masked somewhat by the presence here 5 days prior to this period of a trough which dissipated and now had reformed and was intensifying; thus, the overall change appeared less pronounced than it was actually. Proof of this was indicated by the height departures from normal in excess of 500 ft. in that region within a few hours of the 1500 GMT observations. The downstream movement from wave trough to wave trough had occurred during the preceding 120 hours at a speed slightly above 20 knots while the zonal wind speed for this area during the same period averaged approximately 11 knots, thus indicating it definitely was not phase velocity operating; nor were there any individual troughs or ridges propagating eastward through this region.

By 0900 GMT of August 3, this downstream dispersion of energy had fortified the ridge, as indicated on the Hovmöller diagram at 50° N., 95° W., with the 5-day central height rise of 800 ft. (fig. 1–upper, sector D and fig. 1–lower). This ridge formed a positive barrier against eastward motion of the Low and thus impeded its movement from the States of Washington and Oregon. During this 66-hour period the propagation of amplification or group velocity was 20.5 knots.

From figure 1 upper, sectors E and F, and figure 1 lower, it is readily observed that the downstream dispersion of energy continued to progress eastward along latitude 50° N. However, it should be noted that the speed of increase and subsequent decrease in wave amplitude accelerated considerably during the final few days of the series, the group velocity reaching 28.7 knots during one of these periods.

TABLE 1.—*Speed of downstream dispersion of energy as related to the time of maximum amplification of troughs and ridges*

| Time of maximum intensity (GMT) | Length of period (hours) | Zonal index (kt.) | Group velocity (kt.) | | Phase velocity (kt.) |
|---|---|---|---|---|---|
| | | | Computed | Observed | |
| 0900, July 26 | 60 | 13.8 | 22.5 | 20.0 | 5 |
| 2100, July 28 | 66 | 8.0 | 19.5 | 20.5 | −3.5 |
| 1500, July 31 | 66 | 13.6 | 21.0 | 20.5 | −6.7 |
| 0900, August 3 | 54 | 13.7 | 27.5 | 28.7 | 0 |
| 1500, August 5 | 48 | 16.0 | 28.4 | 25.0 | −3.6 |

Table 1 is based on the time and place of progressive amplification propagated downstream as observed from the troughs and ridges as represented by the Hovmöller chart and the composite 500-mb. chart (fig. 1). The rate of energy dispersion or group velocity is computed by dividing the linear distance between places of amplification of troughs and ridges by the time interval between their occurrences. This table also presents the computed values for the dispersion of energy downstream by use of the formula derived by Rossby [8]:

$$C_g = 2U - C$$

where $U$ represents the zonal speed of the westerlies, $C$ the phase velocity of the planetary wave, and $C_g$ the group velocity. The values of $C_g$ calculated from the zonal wind speed value for 50° N., as computed twice daily by the U. S. Air Force, were compared with the observed progression or retrogression of the troughs and ridges as determined from the 5-day 700-mb. chart prepared by the Extended Forecast Section; the computed and observed values were strikingly similar in practically every case.

These obtained values are in excellent agreement with the findings of Klein [10] for the month of August 1953 when the observed speed averaged near 18 knots for downstream dispersion of energy. Carlin [9] observed and computed speeds of approximately 40 knots or 16° of lat. per day during the winter months, while McQueen and Shellum [11] observed speeds of 26 knots in June 1956. Since the rate of energy dispersion is directly dependent upon the zonal index, and as the zonal index decreases during the summer months, it appears reasonable to expect decreasing values in the speed of downstream dispersion during the summer months.

## 6. STABILITY OF THE AIR MASS

The instability of any cold Low may easily be deduced by observing the cloud types associated with Lows of this classification. However, it was desired in this study to indicate in some quantitative degree the stability or instability accompanying this cold pool. For this purpose the Showalter Stability Index [12] chart prepared twice daily by NWAC was first investigated. This well-known chart depicts the pattern of convective instability, with the +4° C. line representing the approximate border line between stability and instability. The larger the number is algebraically, the greater the stability and the smaller the number, the greater the instability. These charts for the period under study indicated that most of the precipitation area was located within the unstable area. Portions of these charts are illustrated by figures 7 and 8.

However, not completely satisfied with these diagrams of stability, we turned to a new series of investigations by Showalter [13] "The Stability and Thickness Relationships of Two Adjacent Layers." This is a means for easy and rapid presentation of the stability factor and by use of it one can quickly reveal the area of conditional instability. It is thought that a discussion of this relationship and how it is obtained would be beneficial before proceeding with the study.

"The Stability and Thickness Relationship of Two Adjacent Layers," as derived by Showalter comprises the use of thickness charts or individual thickness values, the number of these employed being dependent upon the height to which one desires to compute the stability of the different layers as well as the size of the area covered if individual thickness values are employed. In NWAC the following symbol system is applied:

$Z_{8.5}$ Thickness of the 1000–850-mb. layer
$Z_7$ Thickness of the 1000–700-mb. layer
$Z_5$ Thickness of the 1000–500-mb. layer
$H_0$ Height of the 1000-mb. surface
$H_7$ Height of the 700-mb. surface
$H_5$ Height of the 500-mb. surface

plus similar symbols for other heights and layers. (Henceforth in this article the symbols will be used for the sake of brevity.)

In 1953 Vederman and Smith [14] derived the empirical relationship:

$$H_7 = \left(\frac{H_0 + H_5}{2}\right) + F$$

for the derivation of the $H_7$ chart from the $H_5$ chart. Using summer data they arrived at a value of 600 gpft. for the term $F$. Subsequent statistical and theoretical investigations have revealed that a median value of $F$, adequate both geographically and seasonally, would be 500 gpft.

Interest in considering thickness ratios for other combinations of layers led Showalter to a more formal and complete evaluation of this $Z_7$, $Z_5$ relationship (fig. 9) and the formulation of the following equation:

$$Z_7 - Z_5/2 = +0.05\ Z_7 \pm 0.0212 Z_7$$

While 0.05 $Z_7$ may have a range of values from +405 gpft. to +515 gpft. when the range of the 1000–700-mb. thickness chart is considered, nonetheless the overall median value of +500 gpft. is considered as adequate for practical analysis. The extreme values obtained from ±0.0212 $Z_7$ represent the range to be expected from appli-

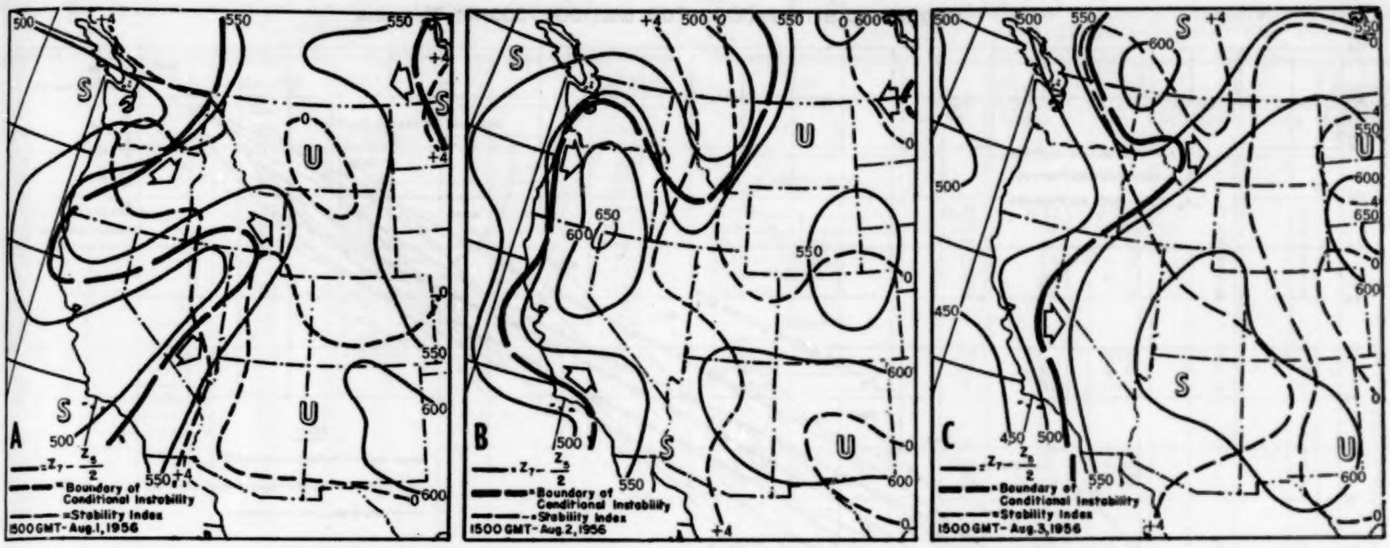



Figure 7.—Synoptic patterns of the stability and thickness relationships of the 1000-700-mb. and 1000-500-mb. layers, August 1–3, 1956. The solid lines indicate values of the quantity $(Z_7-Z_5/2)$ in geopotential feet at 50-ft. intervals. Values below 500-ft. line indicate more stability and values above a trend to greater instability, the end limits being near 250 and 700 feet, respectively. The dashed lines represent the Showalter stability index values in units of 4° C. Values of +4° C. or less tend toward convective instability; those above +4° C. are generally stable. The heavy dashed lines are the limits of conditional instability with the arrows indicating the direction of increasing instability. (A) 1500 GMT, August 1. (B) 1500 GMT, August 2. (C) 1500 GMT, August 3, 1956.

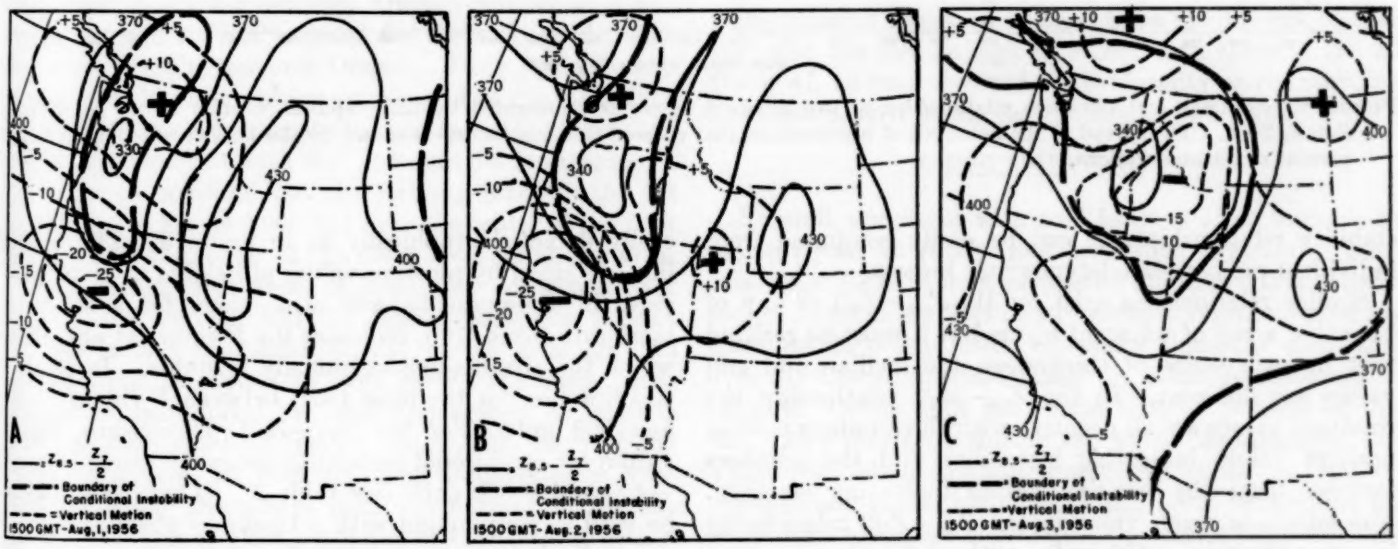



Figure 8.—Synoptic patterns of the stability and thickness relationships of the 1000-850-mb. and 1000-700-mb. layers, August 1–3, 1956. The solid lines indicate values of the quantity $(Z_{8.5}-Z_7/2)$ in geopotential feet at 50-ft. intervals. These values are negative and the mean value between stability and instability is near −400 gpft. Increasing departures from −400 gpft. toward positive numbers represent increasing instability and increasing departures toward more negative values represent increasing stability. The end values are near −250 and −550 feet. The heavy dashed line encloses the area of conditional instability which is always toward smaller negative numbers. Vertical motion (mm. sec.$^{-1}$) as computed by JNWP is shown by short dashed lines with rising vertical motion indicated by a plus sign and sinking or subsiding motion by a minus sign. (A) 1500 GMT, August 1. (B) 1500 GMT, August 2. (C) 1500 GMT, August 3, 1956.

cation of the formula to a stable or unstable lapse rate. And so values of $Z_7-Z_5/2$ greater than 500 gpft. are indicative of a trend toward instability while values less than 500 gpft. represent greater stability. The extreme values of stability for the $Z_7-Z_5/2$ relationship approximate 750 gpft., for which value the lapse rate of the sounding coincides with the dry adiabat, and 250 gpft., for which the lapse rate of the sounding is approximately isothermal.

The actual stability value of these two adjacent layers is easily obtainable from $Z_7$ and $Z_5$ charts by graphical subtraction techniques which permit values for an area the size of facsimile section 1 to be computed in a few minutes. However, if only a small area is desired for the

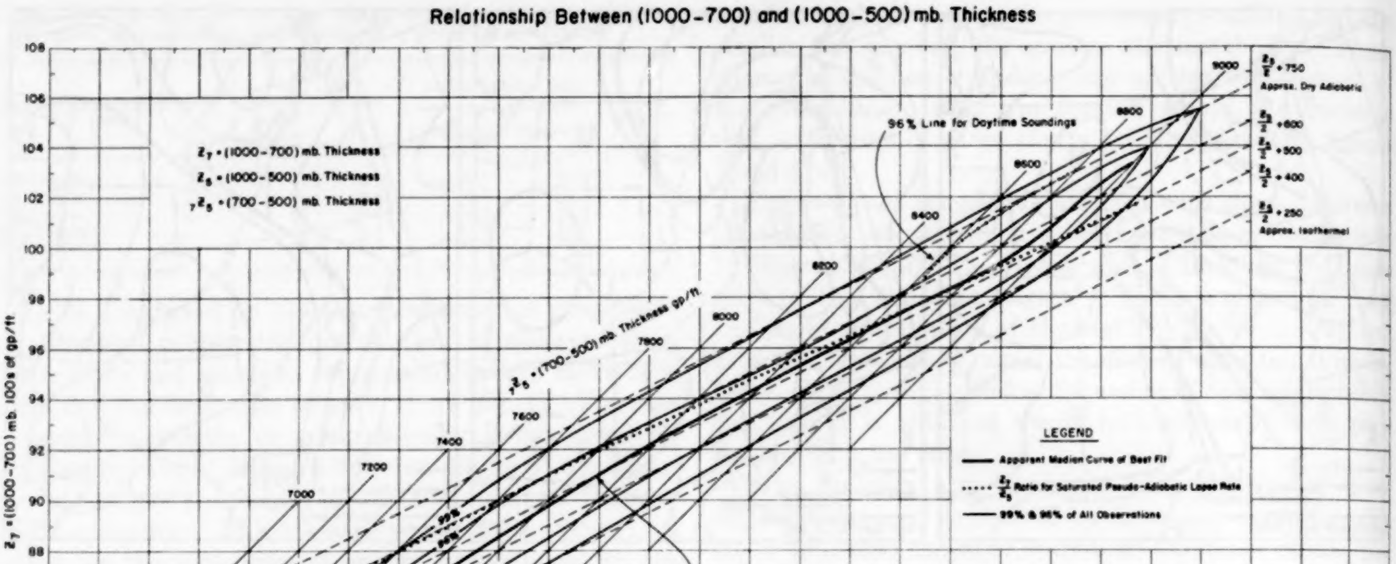



FIGURE 9.—Stability and thickness relationships of two adjacent layers as represented by the graphical solution of the relationship $Z_7 = Z_5/2 + F$. The spread of the hundreds of observations that entered this relationship is shown by the lines enveloping 99 and 96 percent of the observations.

stability relationship this can be easily computed from individual radiosonde teletypewriter reports.

Similar relationships exist for the $Z_{8.5} - Z_7/2$ or any of the other array of adjacent layers but it must be realized that in each series of thicknesses the median and end values are different. In the $Z_{8.5} - Z_7/2$ relationship the resultant values are all negative with the numbers nearest positive values indicating instability and the numbers farthest from the positive values indicating stability. The adequate mean value in the $Z_{8.5} - Z_7/2$ relationship is approximately $-400$ gpft., with the extreme values approaching $-250$ gpft., for which the lapse rate is approximately dry-adiabatic, and $-550$ gpft., for which the lapse rate is approximately isothermal.

From a few of the lines presented in figure 7 it is easily recognized by comparison with the values previously mentioned that for the greater portion of the region from the Rockies to the West Coast the 1000–500-mb. and 1000–700-mb. thickness relationship indicated unstable air with a similar but smaller area of instability indicated by the 1000–700-mb. and 1000–850-mb. thickness relationship. Stability of the soundings above 500 mb. was not computed.

The distribution of the negative and positive areas, as well as the position of the neutral, or 500 gpft., line, is easily depicted graphically as in figure 9. The curved line, obtained by plotting values of heights at given pressures in a pseudoadiabatic atmosphere for a saturated lapse rate (from [15]), indicates the $F$ values at and above which the airmass is conditionally unstable. In figure 9 this line lies, for the most part, between $F$ values of 500 and 600 gpft. For the $Z_{8.5} - Z_7/2$ relationship, the $F$ values for conditional instability generally range between $-400$ and $-300$ gpft. (see table 2). These values must be used in conjunction with a thickness chart and the $F$ chart, for it is at the intersection of the given thickness and $F$ values that the air becomes conditionally unstable.

Even a cursory examination of the charts in figure 7 indicates the relatively good agreement between the two areas of instability, conditional and convective, in the $Z_7 - Z_5/2$ patterns. It can be seen that the areas of instability, although located in the vicinity of the west coast on the 1st, became more inclusive of the States of Washington and Oregon on the 2d as moisture increased (table 4) and heavy rains occurred. It was on the 2d that one of the more intense areas of instability, a closed 650-ft. center, appeared south of Burns, Oreg. This relatively large area of instability replaced the stable air mass that on the 1st had extended across central California into Nevada. By 1500 GMT of the 3d (fig. 7C), both

TABLE 2.—*Intersection values for determination of conditional instability*

| $Z_5$ | $Z_7-Z_5/2$ | $Z_7$ | $Z_{8.5}-Z_7/2$ |
|---|---|---|---|
| 19,300 | 500 | 10,300 | −400 |
| 19,200 | 505 | 10,200 | −395 |
| 19,100 | 505 | 10,100 | −390 |
| 19,000 | 510 | 10,000 | −385 |
| 18,900 | 515 | 9,900 | −375 |
| 18,800 | 520 | 9,800 | −370 |
| 18,700 | 525 | 9,700 | −360 |
| 18,600 | 530 | 9,600 | −355 |
| 18,500 | 535 | 9,500 | −345 |
| 18,400 | 540 | 9,400 | −340 |
| 18,300 | 545 | 9,300 | −330 |
| 18,200 | 550 | 9,200 | −325 |
| 18,100 | 555 | 9,100 | −320 |
| 18,000 | 560 | 9,000 | −315 |
| 17,900 | 565 | 8,900 | −310 |
| 17,800 | 570 | | |
| 17,700 | 570 | | |
| 17,600 | 575 | | |
| 17,500 | 575 | | |
| 17,400 | 580 | | |
| 17,300 | 585 | | |
| 17,200 | 590 | | |
| 17,100 | 595 | | |
| 17,000 | 595 | | |
| 16,900 | 595 | | |
| 16,800 | 595 | | |
| 16,400 | 595 | | |

convective and conditional instability areas had moved eastward from the coastal region but a large area of instability of both types persisted over the Plateau Region and the Rocky Mountain area.

On the lower-level chart showing $Z_{8.5}-Z_7/2$ (fig. 8), conditional instability covered a much smaller area and on the 1st and 2d was confined for the most part to the States of Washington and Oregon. Here again it was inclusive of the region of heavy rain and as the instability area moved north-northeastward on the 3d the attendant precipitation moved with it. It might be interesting at this point to mention that the freezing level on the 1st and 2d was as low as 6,000 feet near the center of the Low and also near the center of this lower-level instability area.

These rather large areas of instability continued over much of the Plateau and the Rocky Mountain regions throughout the remainder of the period although the western limit continued to drift slowly eastward. Numerous thunderstorms or the appearance of distant lightning were recorded during the first six days of the month, and at a few stations more thunderstorms were recorded during those days than was normal for the entire month. Burns, Oreg., was one of the stations with a thunderstorm reported on three separate days during this period. Normally during August only 2 thunderstorms are observed at Burns, Oreg., but during this August there were 7 thunderstorms and 1 night with distant lightning.

Another interesting feature of these charts is the indication of stability over the greater portion of the West by the lower two layers, but instability by the upper two layers. This indicates that most of the thunderstorm activity must have resulted from higher-level instability.

Finally, it might be well to point out another fact that was quite clearly illustrated in the vicinity of Salem, Oreg., on the 3d of the month. On the 2d, as previously mentioned, heavy rain and instability were prevalent over

TABLE 3.—*Precipitation totals and number of thunderstorms August 1–6, 1956*

| Station | Precipitation | Normal precipitation | Deviation | Distant lightning | Thunderstorms | Average no. thunderstorms August |
|---|---|---|---|---|---|---|
| WASHINGTON | | | | | | |
| Seattle | 0.49 | 0.12 | +0.37 | 0 | 0 | 1 |
| Spokane | .38 | .06 | +.32 | 1 | 0 | 2 |
| Stampede Pass | .12 | .26 | −.14 | 0 | 0 | 2 |
| Tatoosh Island | .11 | .36 | −.25 | 0 | 0 | 0 |
| Walla Walla | .40 | .03 | +.37 | 0 | 1 | 2 |
| Yakima | T | .06 | −.06 | 0 | 0 | 1 |
| IDAHO | | | | | | |
| Boise | .02 | 0 | +.02 | 1 | 1 | 3 |
| Lewiston | .07 | .06 | +.01 | 0 | 0 | 3 |
| Pocatello | T | .12 | −.12 | 2 | 2 | 7 |
| MONTANA | | | | | | |
| Helena | .50 | .18 | +.32 | 1 | 4 | 7 |
| Kalispell | .26 | .21 | +.05 | 1 | 3 | 7 |
| Missoula | .25 | .18 | +.07 | 1 | 3 | 6 |
| OREGON | | | | | | |
| Astoria | 1.67 | .24 | +1.43 | 0 | 0 | 0 |
| Burns | .17 | .02 | +.15 | 0 | 3 | 2 |
| Eugene | .41 | .01 | +.40 | 0 | 1 | 1 |
| Meacham | .13 | .06 | +.07 | 0 | 1 | 5 |
| Medford | 0 | .02 | −.02 | 0 | 0 | 1 |
| Pendleton | .36 | .01 | +.35 | 3 | 1 | 3 |
| Portland | 1.06 | .06 | +1.00 | 0 | 0 | 1 |
| Roseburg | .26 | .01 | +.25 | 0 | 1 | 1 |
| Salem | .29 | .06 | +.23 | 0 | 1 | 1 |
| Sexton Summit | 0 | 0 | 0 | 0 | 1 | 1 |

the station. However, on the 3d, even though the soundings indicated moisture values at the fixed levels of 850, 700, and 500 mb. as high or higher than those of the 2d (table 4), no rain occurred in this locality as the stability lines had moved to the eastern border of Oregon.

## 7. PRECIPITATION

Rainfall associated with cold Lows is often variable in amount and intensity and at times practically nonexistent. Nevertheless, experience has shown that usually cut-off Lows in the Washington-Oregon region do produce considerable precipitation especially along the coast and over the Cascades, while inland the totals decrease rather rapidly. Graham [3] has found that 89 percent of the cold Lows that form during the winter months near the Vancouver Island-Washington-Oregon coastline produce precipitation in southern California. And so it would be reasonable to expect considerable precipitation from this type of Low to the north of California during the summer months. Table 3 shows that this storm was no exception to these expectations. The heavier totals did occur along or near the coastal sections of Oregon with Astoria receiving 1.67 inches and Portland 1.06 inches.

It was thought interesting to compare the moisture values of various levels in the upper-air soundings in the vicinity of the cold Low to ascertain the changes that occurred from day to day while it was practically stationary and also changes that occurred later along its path. Therefore the differences between the dry-bulb temperatures and the dewpoint temperatures were obtained for 850-mb., 700-mb., and 500-mb. heights; these values are shown in table 4. The occurrence of moderate or heavy

Table 4.—*Dewpoint depression (° C.) at fixed pressure levels, 0300 and 1500 GMT, August 1–5, 1956.*

| Station | Level (mb.) | Aug. 1 03 | Aug. 1 15 | Aug. 2 03 | Aug. 2 15 | Aug. 3 03 | Aug. 3 15 | Aug. 4 03 | Aug. 4 15 | Aug. 5 03 | Aug. 5 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tatoosh Island, Wash | 850 | 3 | 4 | 5 | 2 | 4 | 4 | 2 | 4 | 6 | 5 |
| | 700 | 16 | 10 | 3 | 1 | 11 | 10 | 5 | M | 7 | 10 |
| | 500 | 7 | 11 | 8 | 5 | 12 | 14 | 10 | 9 | 10 | 14 |
| Seattle, Wash | 850 | 4 | 1 | 4 | 1 | 2 | 2 | 3 | 4 | 6 | 6 |
| | 700 | 17 | 17 | 5 | 2 | 2 | 5 | 7 | 8 | 9 | 15 |
| | 500 | 3 | 4 | 3 | 6 | (*) | M | 15 | 12 | 13 | 14 |
| Salem, Oreg | 850 | 4 | 2 | 2 | 3 | 2 | ---- | 2 | 4 | 5 | ---- |
| | 700 | 8 | 12 | 3 | 5 | 1 | ---- | 7 | 1 | 12 | ---- |
| | 500 | 4 | 3 | 10 | 6 | *M | ---- | 2 | 5 | 11 | ---- |
| Medford, Oreg | 850 | 9 | 2 | 4 | 3 | 8 | 6 | 10 | 4 | 6 | 5 |
| | 700 | 10 | 6 | 1 | 13 | 9 | 15 | 15 | 5 | 3 | 3 |
| | 500 | M | M | M | 10 | M | 8 | 5 | 11 | 10 | 7 |
| Spokane, Wash | 850 | 22 | 22 | 4 | 5 | 8 | 0 | 11 | 8 | 10 | 11 |
| | 700 | 16 | 15 | 10 | 5 | 3 | 0 | 3 | 17 | 16 | 8 |
| | 500 | 14 | 5 | 15 | 14 | *13 | *8 | M | 15 | 4 | 10 |
| Great Falls, Mont | 850 | 17 | 15 | 10 | 5 | 5 | 8 | 15 | 15 | 21 | 12 |
| | 700 | 7 | 10 | 10 | 9 | 7 | 8 | 10 | 15 | 11 | 7 |
| | 500 | 13 | M | 2 | 10 | *M | *M | 11 | 12 | 8 | 3 |
| Edmonton, Alberta | 850 | 6 | 9 | 4 | 7 | 7 | 2 | 9 | 2 | 4 | 8 |
| | 700 | 3 | 5 | 10 | 6 | 14 | 0 | 5 | 2 | 2 | 3 |
| | 500 | 4 | 6 | 8 | 15 | 13 | 16 | M | 9 | 3 | 3 |
| Boise, Idaho | 850 | 23 | 13 | 15 | 10 | 13 | 15 | 20 | 23 | 24 | 15 |
| | 700 | 16 | 14 | 10 | 12 | 11 | 8 | 13 | 14 | 14 | 12 |
| | 500 | M | M | M | M | 3 | 8 | 11 | 3 | 3 | M |
| Ogden, Utah | 850 | 12 | 9 | 26 | 8 | 24 | 12 | 19 | 23 | 27 | 28 |
| | 700 | 5 | 12 | -- | 18 | 19 | 16 | 15 | 18 | 14 | 21 |
| | 500 | 2 | M | 8 | 4 | 5 | 11 | 15 | 9 | 3 | M |

Oakland Calif. Very dry all levels.
Winnemucca, Nev. Very dry most levels.
Lander, Wyo. Generally dry 700 mb. or lower.

Note: Two levels underscored indicates moderate rain within next 12 hours. Three levels underscored indicates heavy rain within 12 hours.
*Depression <5° C. at 600 mb. but dries before reaching 500-mb. height.
M=Motorboating.

Table 5.—*Departure of daily maximum and minimum temperature (° F.) from normal, August 2–4, 1956*

| Station | August 2 Min. | August 2 Max. | August 3 Min. | August 3 Max. | August 4 Min. | August 4 Max. |
|---|---|---|---|---|---|---|
| Seattle | −4 | −21 | −8 | −7 | −5 | −2 |
| Spokane | −14 | −19 | −13 | −18 | −12 | −9 |
| Stampede Pass | −9 | −19 | −9 | −14 | −5 | −4 |
| Tatoosh Island | −3 | −2 | −5 | −2 | −4 | −3 |
| Walla Walla | −10 | −22 | −12 | −16 | −8 | −10 |
| Yakima | −14 | −18 | −4 | −13 | −8 | −10 |
| Boise | −14 | −22 | −13 | −11 | −7 | −8 |
| Lewiston | −16 | −25 | −15 | −15 | −13 | −9 |
| Pocatello | −4 | −12 | −7 | −10 | −9 | −2 |
| Great Falls | −1 | −8 | −? | −12 | −3 | −3 |
| Helena | +4 | −3 | −3 | −8 | −8 | −4 |
| Kalispell | −10 | −16 | −16 | −20 | −24 | −11 |
| Missoula | −2 | −22 | −8 | −18 | −11 | −10 |
| Burns | −7 | −22 | −14 | −13 | −3 | −8 |
| Meacham | −13 | −22 | −8 | −14 | −6 | −9 |
| Medford | −11 | −18 | −12 | −15 | −7 | −10 |
| Pendleton | −9 | −21 | −9 | −15 | −1 | −11 |
| Portland | −2 | −23 | −1 | −14 | −4 | −5 |
| Roseburg | −14 | −16 | −13 | −5 | −5 | −7 |
| Salem | −2 | −21 | +1 | −10 | −1 | −5 |
| Sexton Summit | −13 | −15 | −8 | −12 | −4 | −13 |
| Blue Canyon | −14 | −13 | −11 | −10 | −13 | −12 |
| Eureka | −3 | −1 | −2 | −8 | +1 | −1 |
| Mt. Shasta | −5 | −19 | −11 | −8 | −9 | −8 |
| Oakland | −2 | 0 | −2 | −7 | 0 | −12 |
| Redbluff | −2 | −11 | −5 | −9 | −8 | −13 |
| Sacramento | −4 | −6 | −2 | −6 | −6 | −12 |
| Elko | −13 | −16 | −17 | −10 | −12 | −7 |
| Ely | −14 | −7 | −15 | −9 | −14 | −9 |
| Reno | −10 | −13 | −10 | −9 | −10 | −12 |
| Winnemucca | −7 | −15 | −21 | −8 | −9 | −5 |
| Salt Lake City | −1 | 0 | −15 | −6 | −7 | −3 |

precipitation during or within 12 hours following the sounding is indicated in the table by underscoring the values for that sounding. Heavy rain, in this section and for this season of the year, was defined as a 12-hour total three or more times the normal 24-hour amount. It should be noted that only when the dewpoint depression was near 5° C. or less did moderate to heavy rain occur, and in practically all cases for heavy rain these values had to exist to at least 600 mb. It was also noted that the occurrence of most precipitation was associated with 850-mb. dewpoint values of from +2° to +5° C. In several instances precipitation did not occur even though the moisture content was relatively high at two or three levels. In these cases, it appears that the center of the Low had become removed from this zone of moisture by several hundred miles, and the instability associated with the storm had diminished, thus hindering the production of precipitation. In this regard, attention is directed to figure 7C which clearly defines the area of convective and conditional stability as east of Salem, Oreg., at a time when the air at that station contained high moisture content; precipitation did not occur.

Table 6.—*Temperature (° C.) at 5 km., August 1–4, 1956*

| Station | August 1 0300 | August 1 1500 | August 2 0300 | August 2 1500 | August 3 0300 | August 3 1500 | August 4 0300 | August record from [17] | Years of record in [17] |
|---|---|---|---|---|---|---|---|---|---|
| Boise | −6 | −8 | −10 | −11 | −17 | −11 | −10 | −18 | 7 |
| Ely | −5 | −5 | −6 | −7 | −8 | −8 | −8 | −12 | 7 |
| Great Falls | −8 | −9 | −8 | −7 | −8 | −9 | −12 | −14 | 6 |
| Medford | −10 | −16 | −20 | −17 | −11 | −9 | −11 | −15 | 7 |
| Oakland | −5 | −6 | −8 | −6 | −8 | −6 | −9 | −11 | 10 |
| Ogden | −5 | −7 | −6 | −6 | −7 | −9 | −6 | −7 | 3 |
| Seattle | −16 | −17 | −19 | −17 | −18 | −16 | −14 | −22 | 11 |
| Spokane | −12 | −12 | −13 | −14 | −16 | −19 | −15 | −18 | 12 |
| Tatoosh Island | −17 | −18 | −16 | −14 | −15 | −17 | −13 | −15 | 12 |

The use of the term "heavy precipitation" to describe the rainfall over most of the States of Washington, Oregon, and western Idaho during the 5-day period August 1–5, is entirely in accord with the class limit values used in the 5-day forecast period. Figure 3B of the preceding article by Andrews [16] clearly indicates that this rain made an important contribution to the total precipitation for August, for there were only two rainy periods during August with both of about equal intensity at many of the stations.

## 8. TEMPERATURE DEVIATIONS

That both the maximum and minimum temperatures reported by the first order stations during the period of August 1 to 5, 1956, were much below normal is shown in table 5. In this table the entire period was not included but a sufficient interval was indicated to note the scope of the temperature deviations. Lewiston, Idaho reported the greatest departure of maximum temperature in the period on August 2, a reading which was 25° F. below the normal high for that date. But it will be noticed that numerous other departures in excess of 19° F. were observed. The greatest anomaly in relation to minimum temperatures was recorded at Kalispell, Mont. where the minimum of August 4 was 24° F. below normal.

Another indication as to the intensity of the cold air associated with the cold pool is presented in table 6 which

lists the 5-km. temperature observed August 1–4 and the extreme minimum 5-km. values for August as reported in [17]. It is realized that the minimum values presented in [17] are, in many cases, from short-period records, and in only a few instances do they represent a decennium. However, it will be noted in table 6 that Medford, Oreg. at 0300 GMT August 2 had a temperature of −20° C. at 5 km. which was 5° C. below the extreme value (period: September 1939 to December 1945). At Oakland, Calif., well to the south of the cold pool center, the temperature at 0300 GMT of the 4th was within 2° of the low for August obtained in a period of record from September 1936 to December 1945. Spokane, Wash. reported, at the same level, a reading of 1° C. below the low that was established during the period from July 1934 to December 1945.

A summation of the departures from normal of temperatures that occurred during the interval of August 1–5, is presented in figure 10 which clearly depicts the fact that the region had much below [1] the normal average temperature during that period. Absolute values are not indicated but the zone encompassed by the two shaded areas experienced an accumulated total of 25° F. or more below the daily normal for those 5 days. The area of inner shading represents an aggregate deviation of 50° F. or more during the same 5 days. The station with the greatest deviation sum during the 5 days was Lewiston, Idaho with a total of 71° F. indicating that during August 1–5 the maximum and minimum readings at Lewiston averaged approximately 15° below normal each day. The temperature anomaly for August (see Andrews, fig. 2B, p. 307 of this issue) indicates that the Western States recovered from these low temperatures to a considerable extent prior to the end of the month.

## 9. SURFACE TEMPERATURES AND THICKNESS RELATIONSHIPS

It is generally believed that a definite relationship exists between the surface temperatures and the thickness of the overlying layer, and indeed under certain conditions the correlation between areas of anomalous thickness and areas of anomalous maximum or minimum temperatures appears to be quite good. Because the departures from normal maximum and minimum temperatures were extremely large during several days of the period of this study it was thought that a presentation of the temperature relationship to the departure from normal thickness as obtained from the NWAC 30-hour 1000-500-mb. prognostic thickness chart would be informative. The actual observed isopleths of thickness departures from normal are not presented in this study but the area and intensity of the departures from normal 500-mb. height (fig. 2B to 6B) were in close propinquity with the thickness departures from normal and may be used for comparative purposes.

[1] This value, approximately 5° F. per day departure, was ascertained as the value used by the Extended Forecast Section in that region during the month of August for their class limits of "much below normal".

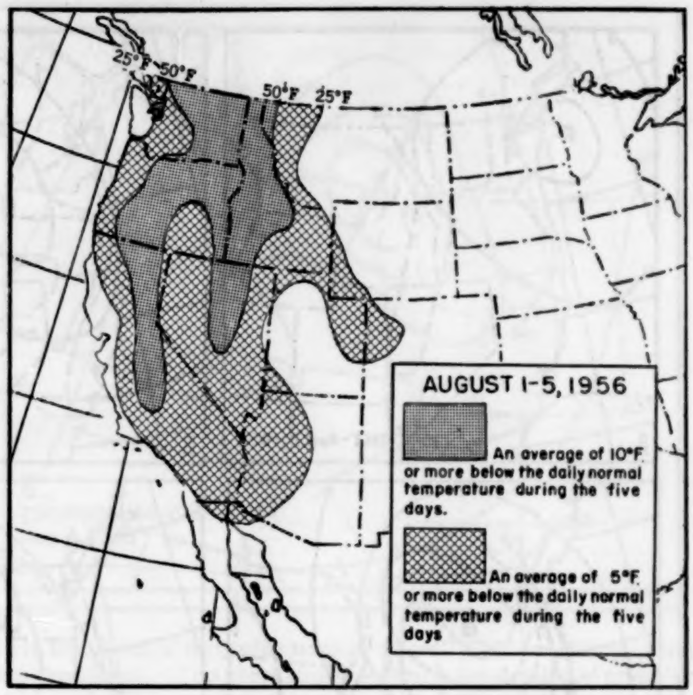



FIGURE 10.—Total temperature deviation from normal in ° F. for the 5-day period August 1–5, 1956. The entire shaded area averaged 5° F. or more per day below the normal August daily average temperature during this 5-day period. (5° F. was used since this is the approximate class limit value used by Extended Forecast Section in this area during August to represent much below normal temperatures.) The inner shaded area averaged 10° F. or more per day below the normal daily average with the maximum departure approaching −15° F. per day at Lewiston, Idaho.

In a case study on this subject, Kibler, Lennahan, and Martin [18], and in later research Allen and Ellis [19], found that this relationship is somewhat dependent upon the physical and geographical location of the station as well as the season of the year. For example, large water bodies tend to influence the temperature values by their moderating effect. There was some indication that during periods of large thickness and high temperature, deviations from the regression line tended to be greater than under conditions of low thickness and low temperature.

A higher correlation between thickness and surface temperature might be expected when there is good air movement and also when the ground covering remains uniform over the season for which the relationship is computed.

There are many other factors that enter into this problem of forecasting the maximum and minimum temperature from the deviation of thickness from normal. One of the most troublesome of these is the fact that the maximum or minimum temperature may occur at any time during the 24 hours, possibly as much as 12 to 18 hours prior to or after the normal time of maxima or minima. Thus an individual maximum or minimum temperature may not be related to the current airmass over the station

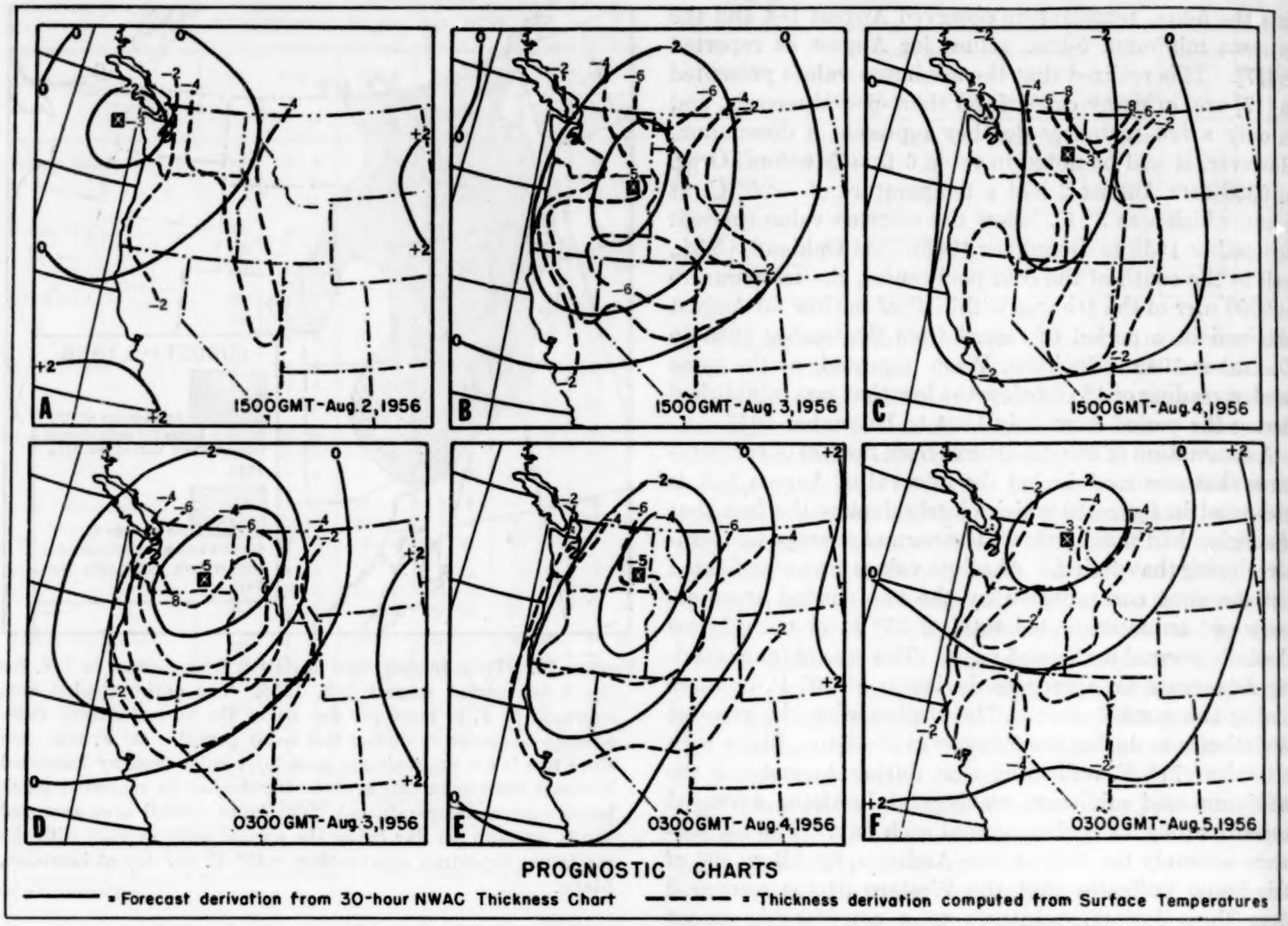



FIGURE 11.—Composite charts consisting of the 30-hour prognostic 1000-500-mb. ($Z_5$) thickness anomalies (solid lines) as derived from the $Z_5$ thickness prognoses and the normal thickness chart for August, and the actual deviations of temperature maxima or minima from normal converted into quasi-thickness isopleths (dashed lines). This furnishes a picture of the relationship between the deviations of temperature and deviations of thickness. Actual thickness values are not presented but as previously stated are similar in area covered and value to the departure from normal height in this study. Generally in these charts the relationships of departures of temperatures to $Z_5$ departures are in quite good agreement as to intensity and area covered. (A) 1500 GMT, August 2. (B) 1500 GMT, August 3. (C) 1500 GMT, August 4. (D) 0300 GMT, August 3, (E) 0300 GMT, August 4. (F) 0300 GMT, August 5, 1956. Parts A, B, and C employ minimum temperatures; parts D, E, and F, maximum temperatures.

at the time of the prognostic chart but to a later outbreak of cold air or influx of warm air. Hence the correlation may be improved if a concurrent surface temperature is used instead of the maximum or minimum. In a 36-hour prognostic thickness chart, the indicated departure from normal would be applicable in the forecasting of maxima or minima at times a short period in advance, but future modification would have to be employed for the forecast to be extended beyond that time.

Minimum and maximum temperatures are also frequently affected by local cloud cover, drainage winds, and other orographic factors, hence a generally applicable relationship between the departures from normal thickness and anomalous daily temperature extremes will not likely be found. However, over much of the country, the surface temperature extremes are influenced by the mean temperature of the overlying airmass to a greater extent than by any other factor, and the areas of thickness departure from normal provide a definite guide in forecasting temperature anomalies. Some of the problems with regard to large positive anomalies of thickness were discussed by McQueen and Shellum [11].

Charts illustrating the departure of the prognostic 1000-500-mb. thickness from normal as prepared twice daily by NWAC are shown by the solid lines in figure 11. In figure 11, parts A, B, and C, are for the approximate time of the minimum temperature and parts D, E, F, are for the time of the maximum for August 2, 3, and 4. It will be noted that the dashed lines represent pseudo-thickness lines obtained by converting the anomalies of maximum and minimum temperatures at each first order station into thickness deviation lines by using 5.4° F. as

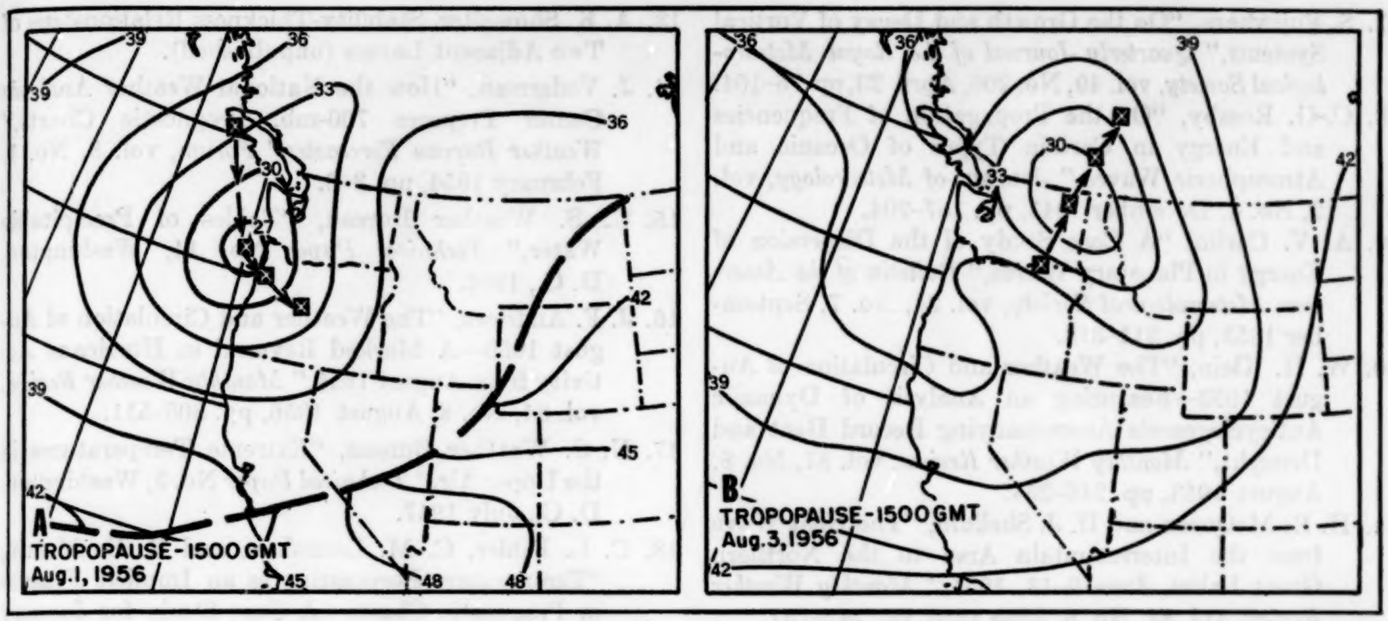



FIGURE 12.—Tropopause height charts over the Western States (labeled in thousands of feet) with track of 12-hour positions of tropopause minimum. (A) 1500 GMT, August 1, 1956. Heavy line is tropopause break line. This chart clearly indicates the depth and intensity of the cold air which lowered the height of the tropopause to 26,000 feet at the center on this date. (B) 1500 GMT August 3, 1956. Note the persistency of this cold pool and the little modification that ensued. This pool of cold air was easily followed for the next several days as it drifted northward and eastward across Canada.

the relationship for each 200 ft. of thickness, since mean temperature changes of this magnitude are equivalent to 200-ft. changes in 1000-500-mb. thicknesses.

It is readily apparent that the forecast thickness anomaly and the observed pseudo-thickness in nearly all cases were in close relationship to each other. It may also be seen, by use of the height anomalies as a fairly good approximation of the thickness anomalies in this study, that the pseudo-thickness lines obtained from the temperatures are in contiguity with the height anomalies.

## 10. TROPOPAUSE

Because the center of the cold Low was poorly defined from the surface analysis it was thought that its definition on the NWAC tropopause height charts would be of interest. Two of these charts at 48-hour intervals are reproduced in figure 12. They clearly indicate that the cold pool was well-defined in the upper levels of the atmosphere with the tropopause surface near 26,000 ft. at 1500 GMT of August 1, 1956. This may be among the lowest tropopauses to have occurred in that region during the month of August, although comparative data are not available for checking this possibility. The 5-km. temperatures were near or at record low values during this time and there appeared to be but minor changes of lapse rate between that level and the 8-km. level which was the approximate height of the tropopause on August 1.

During the period under study the tropopause minimum remained about vertically above and below the low centers on the constant pressure charts and its sequence of motion was in agreement with the motion of the low centers at other levels. After 1500 GMT of August 3, there was gradual filling of the cold pool with attendent temperature modification; for example, the temperature of −50° C., at 26,000 ft. on August 1, was associated with heights of about 35,000 ft. by August 5.

## ACKNOWLEDGMENTS

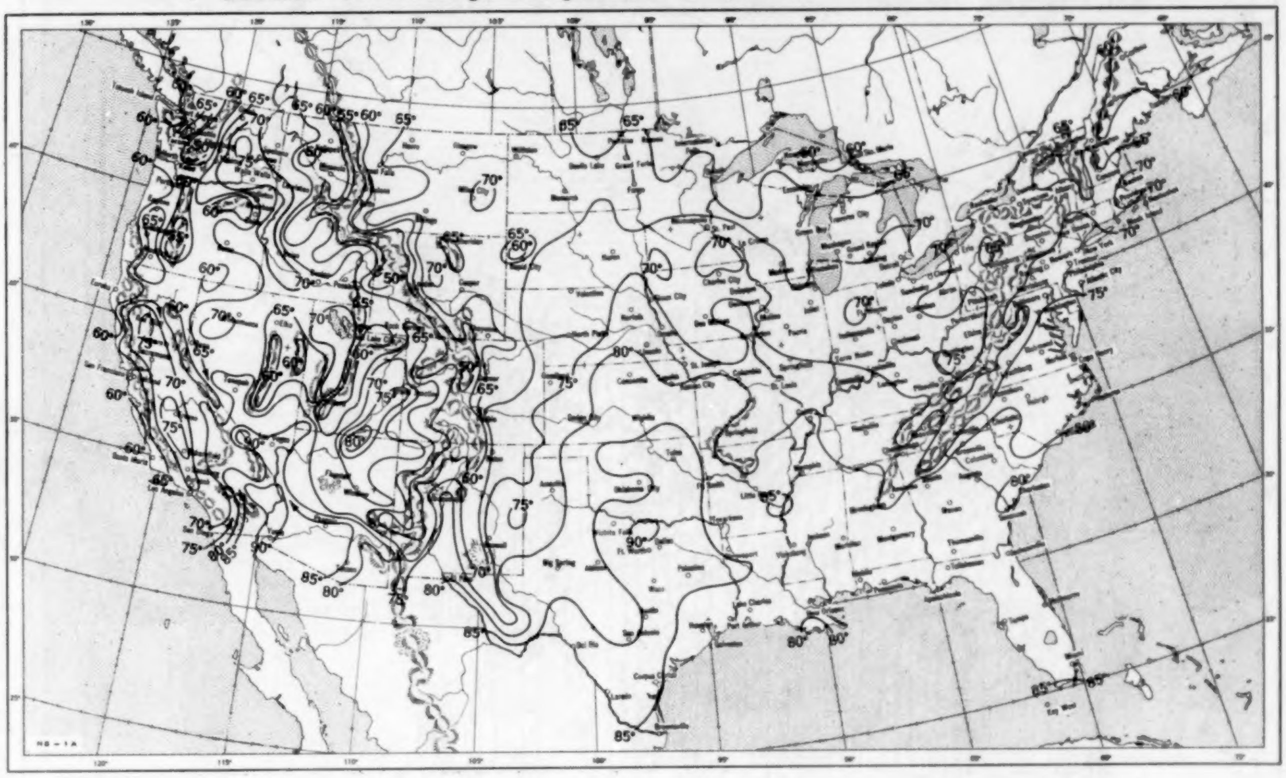
The writers wish to express their appreciation to the staff members of NWAC for helpful suggestions and the reviewing of the article, and to the Daily Map Unit of the Weather Bureau for detailed drafting of the figures.

## REFERENCES

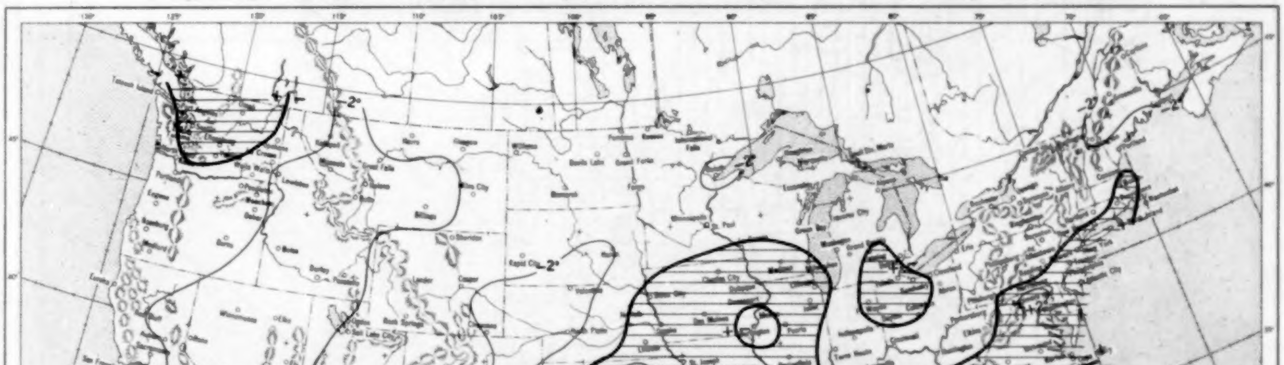
1. E. J. Sumner, "Cold Pools: A Statistical and Synoptic Study," *The Meteorological Magazine*, vol. 82, No. 976, October 1953, pp. 291–301.
2. E. Hovmöller, "The Trough-and-Ridge Diagram," *Tellus*, vol. 1, No. 2, May 1949, pp. 62–66.
3. R. D. Graham, Cold Low Aloft Project, U. S. Weather Bureau, unpublished progress report.
4. E. Palmén and K. M. Nagler, "The Formation and Structure of a Large-Scale Disturbance in the Westerlies," *Journal of Meteorology*, vol. 6, No. 4, August 1949, pp. 227–242.
5. S. Petterssen, *Weather Analysis and Forecasting*, First Edition, McGraw-Hill Book Co., Inc., 1940, pp. 437–439.
6. S. Petterssen, *Weather Analysis and Forecasting*, Second Edition, vol. 1, McGraw-Hill Book Co., Inc., 1956, pp. 36–41.

7. S. Fujiwhara, "On the Growth and Decay of Vortical Systems," *Quarterly Journal of the Royal Meteorological Society*, vol. 49, No. 206, April 23, pp. 75–104.
8. C.-G. Rossby, "On the Propagation of Frequencies and Energy in Certain Types of Oceanic and Atmospheric Waves," *Journal of Meteorology*, vol. 2, No. 4, December 1945, pp. 187–204.
9. A. V. Carlin, "A Case Study of the Dispersion of Energy in Planetary Waves," *Bulletin of the American Meteorological Society*, vol. 34, No. 7, September 1953, pp. 311–318.
10. W. H. Klein, "The Weather and Circulation of August 1953—Featuring an Analysis of Dynamic Anticyclogenesis Accompanying Record Heat and Drought," *Monthly Weather Review*, vol. 81, No. 8, August 1953, pp. 246–254.
11. H. R. McQueen and H. J. Shellum, "The Heat Wave from the Intermountain Area to the Northern Great Lakes, June 9–13, 1956," *Monthly Weather Review*, vol. 84, No. 6, June 1956, pp. 242–251.
12. A. K. Showalter, "A Stability Index for Thunderstorm Forecasting," *Bulletin of the American Meteorological Society*, vol. 34, No. 6, June 1953, pp. 250–252.
13. A. K. Showalter, Stability-Thickness Relationships of Two Adjacent Layers (unpublished).
14. J. Vederman, "How the National Weather Analysis Center Prepares 700-mb. Prognostic Charts," *Weather Bureau Forecasters' Forum*, vol. 8, No. 1, February 1956, pp. 3–6.
15. U. S. Weather Bureau, "Tables of Precipitable Water," *Technical Paper* No. 14, Washington, D. C., 1951.
16. J. F. Andrews, "The Weather and Circulation of August 1956—A Marked Reversal in Hurricane Activity from August 1955," *Monthly Weather Review*, vol. 84, No. 8, August 1956, pp. 305–311.
17. U. S. Weather Bureau, "Extreme Temperatures in the Upper Air," *Technical Paper* No. 3, Washington, D. C., July 1947.
18. C. L. Kibler, C. M. Lennahan, and R. H. Martin, "Temperature Forecasting as an Implicit Feature in Prognostic Charts—A Case Study for January 23–31, 1955," *Monthly Weather Review*, vol. 83, No. 1, January 1955, pp. 23–30.
19. R. A. Allen and J. O. Ellis, personal communication.

## Chart I. A. Average Temperature (°F.) at Surface, August 1956.

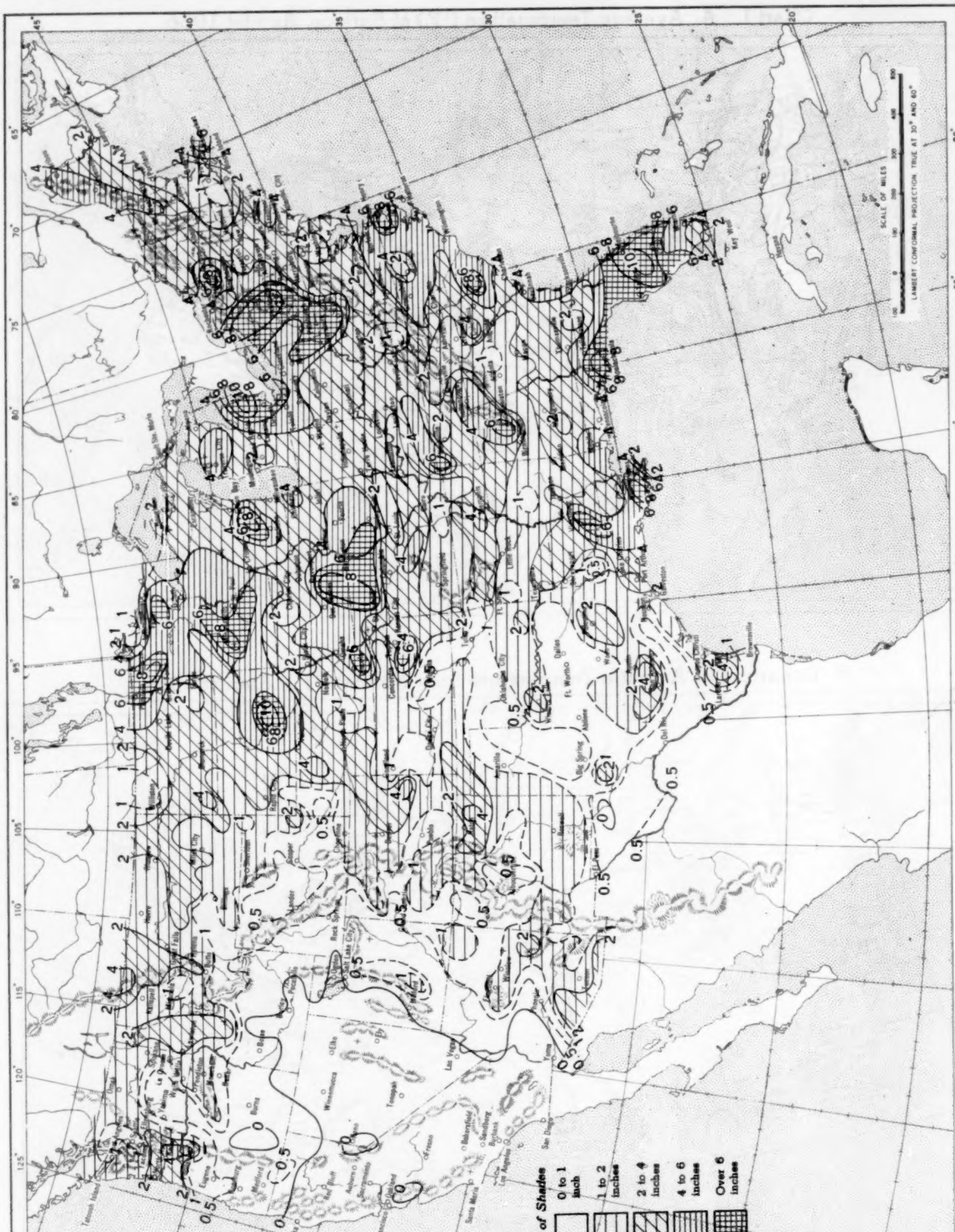


## B. Departure of Average Temperature from Normal (°F.), August 1956.



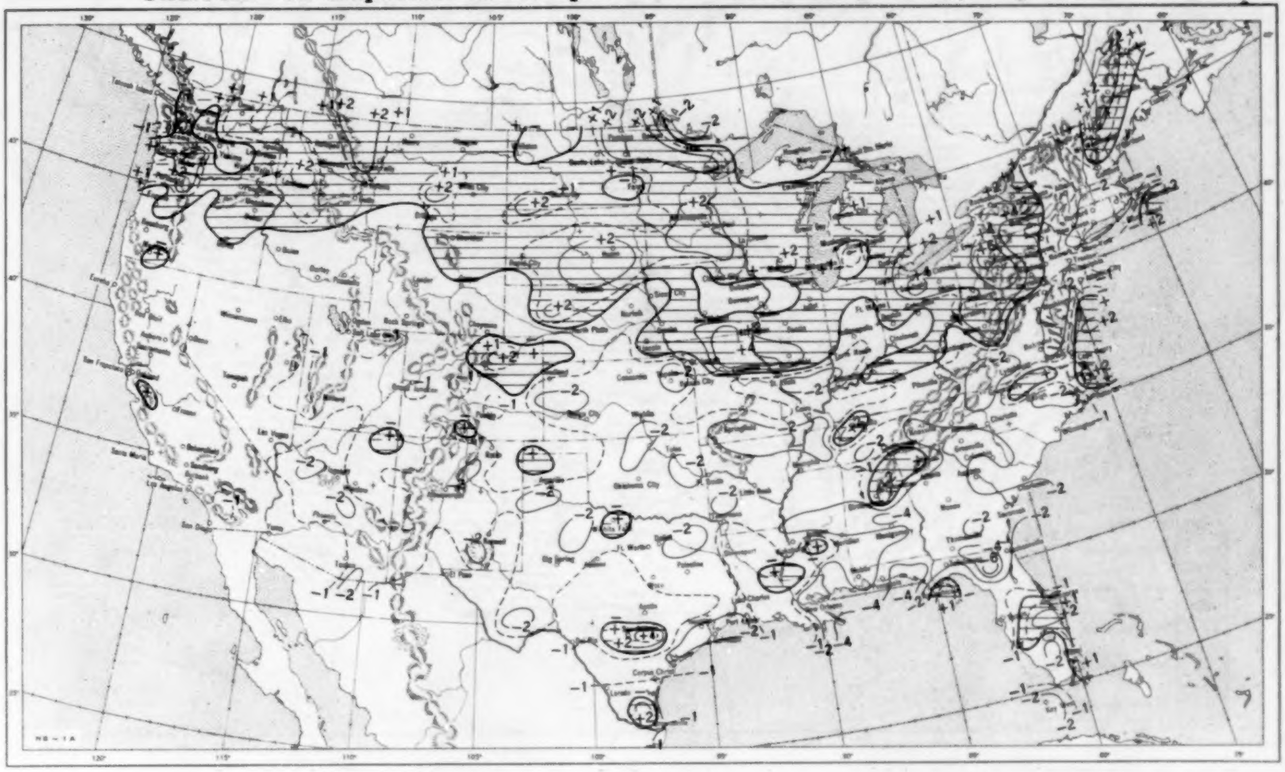
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), August 1956.

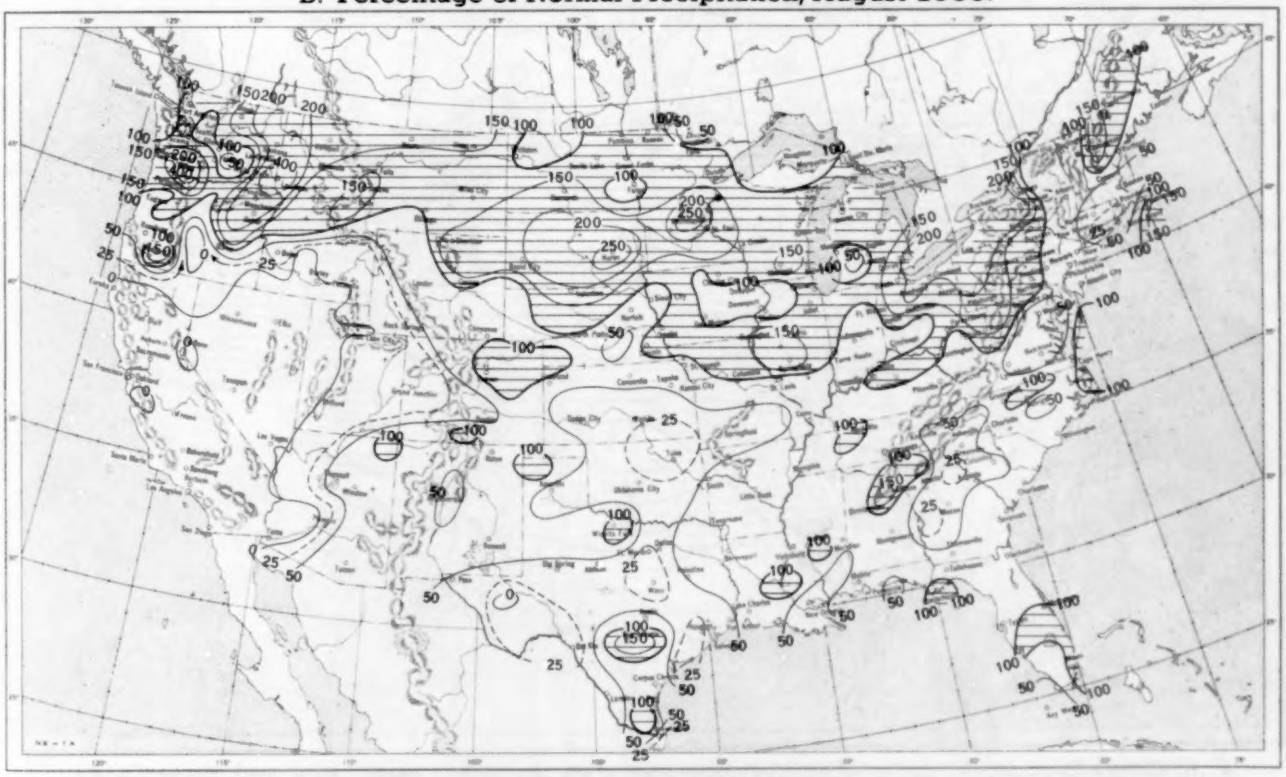



Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), August 1956.

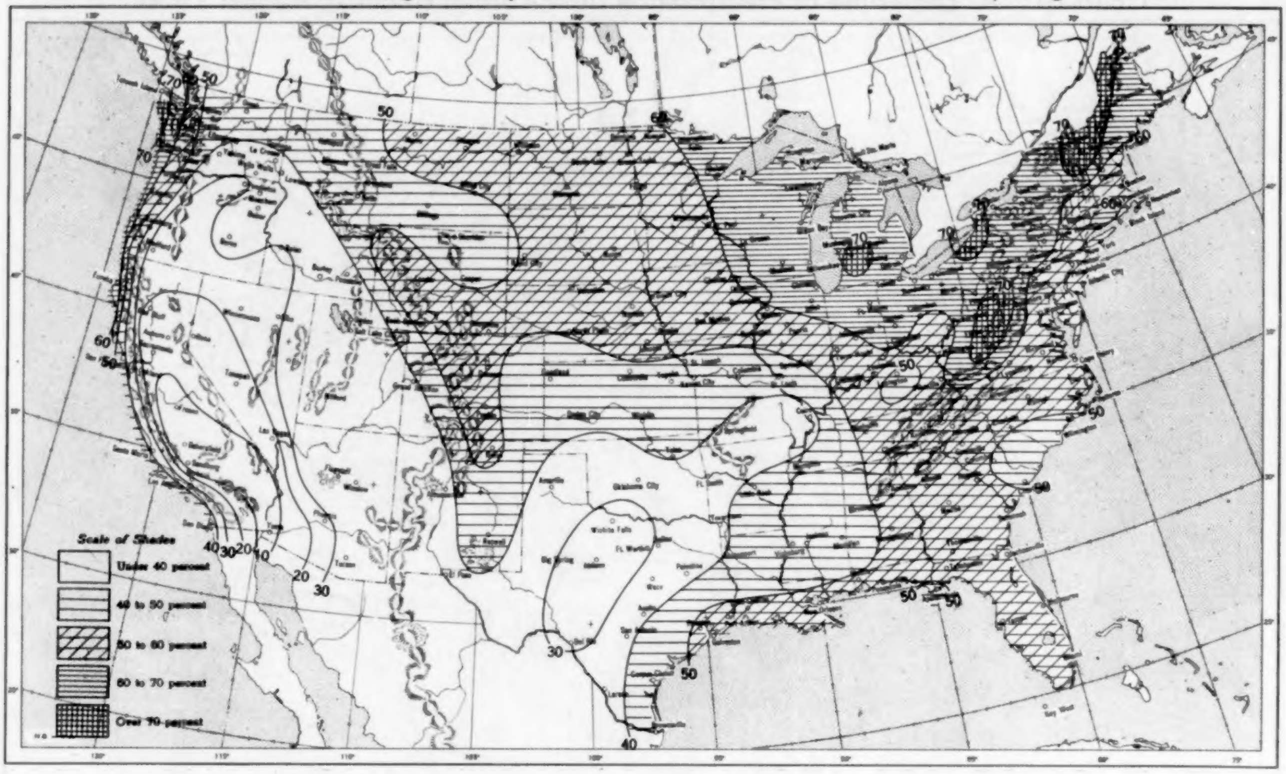


B. Percentage of Normal Precipitation, August 1956.

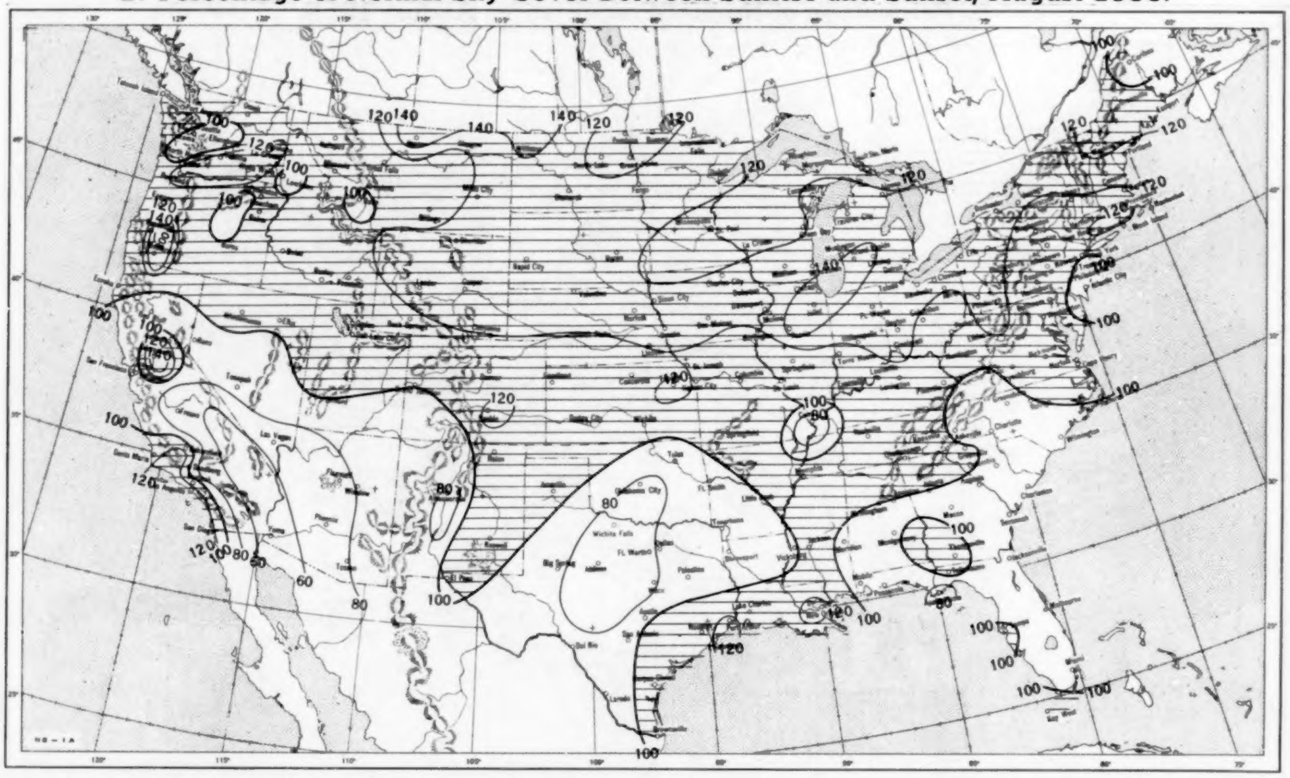


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

## Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, August 1956.

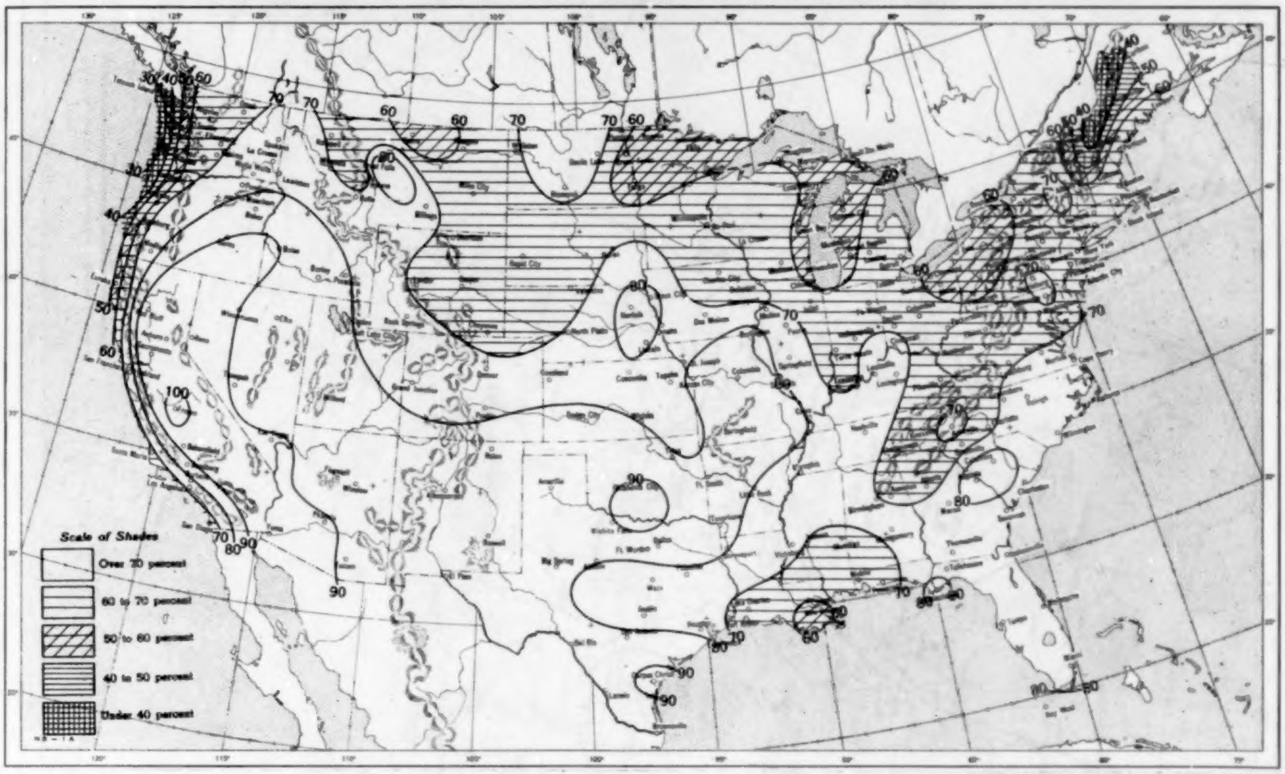



## B. Percentage of Normal Sky Cover Between Sunrise and Sunset, August 1956.

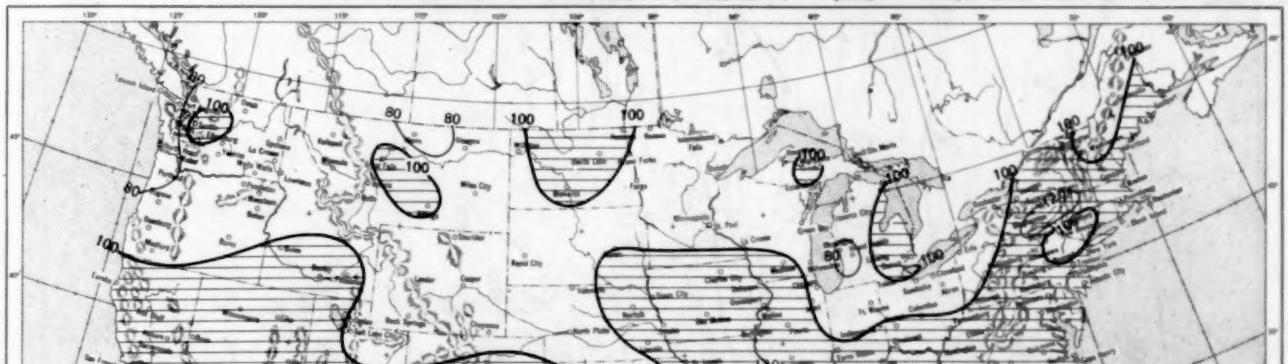


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

## Chart VII. A. Percentage of Possible Sunshine, August 1956.




## B. Percentage of Normal Sunshine, August 1956.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, August 1956. Inset: Percentage of Mean Daily Solar Radiation, August 1956. (Mean based on period 1951-55.)

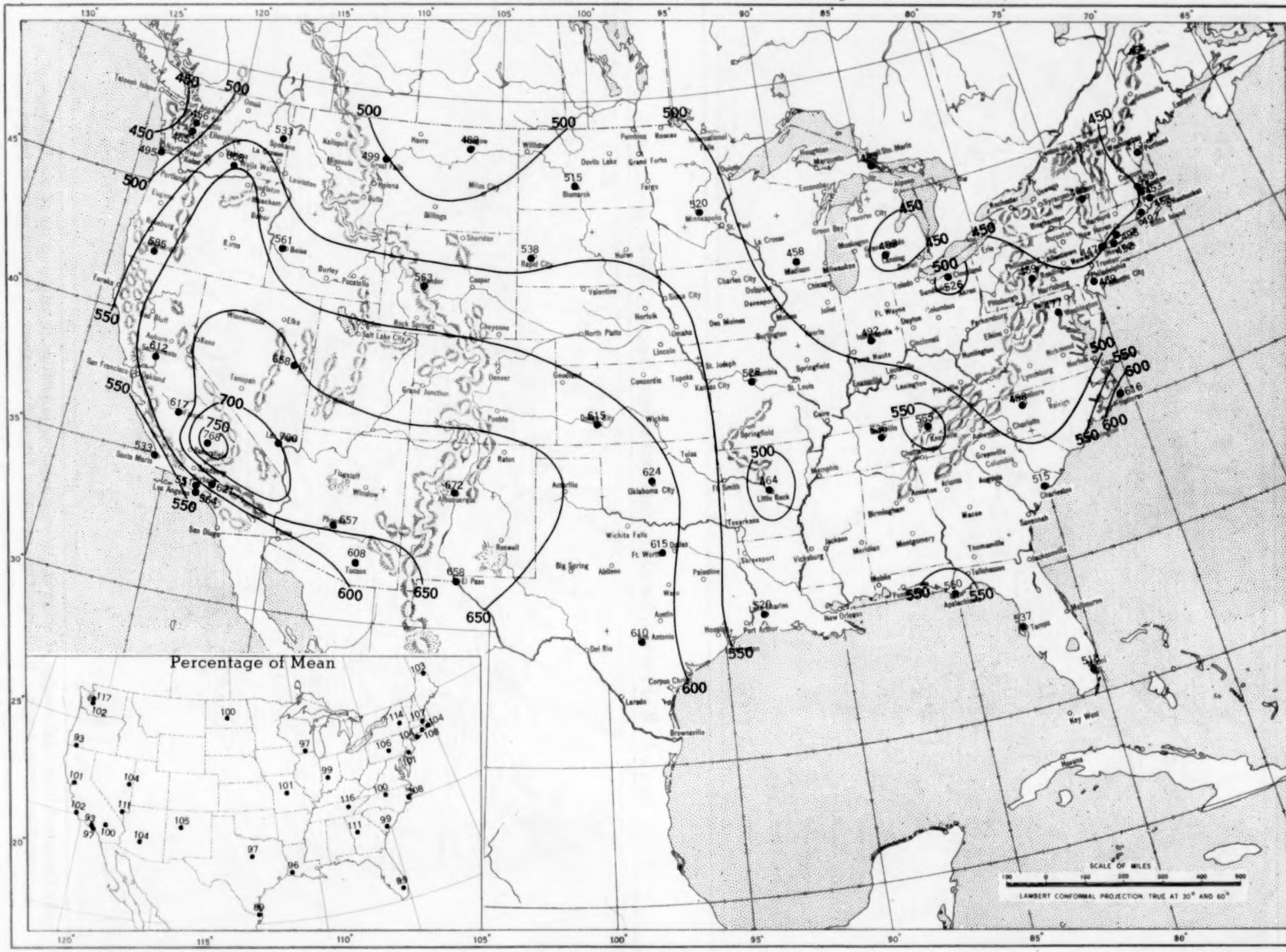
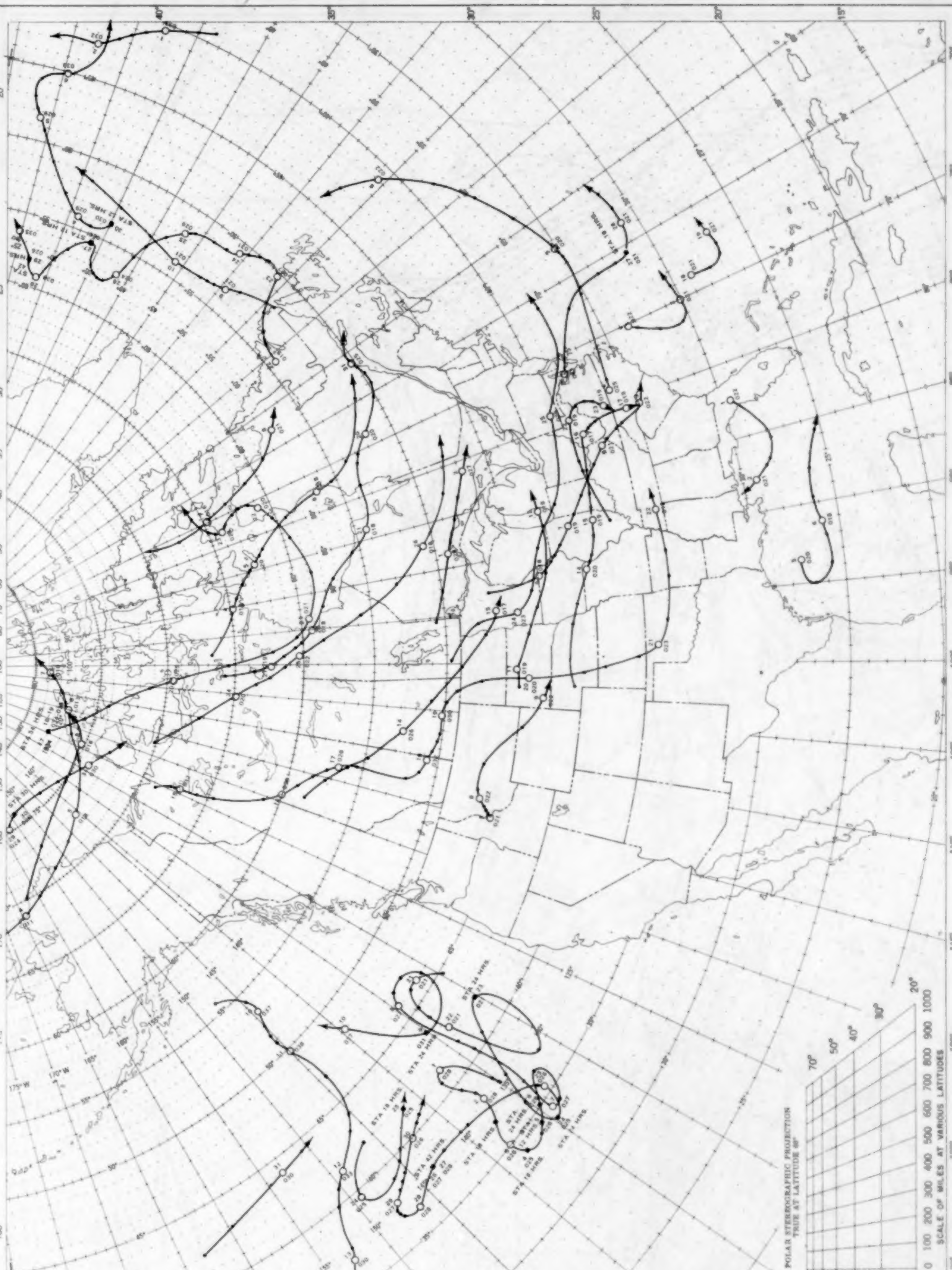


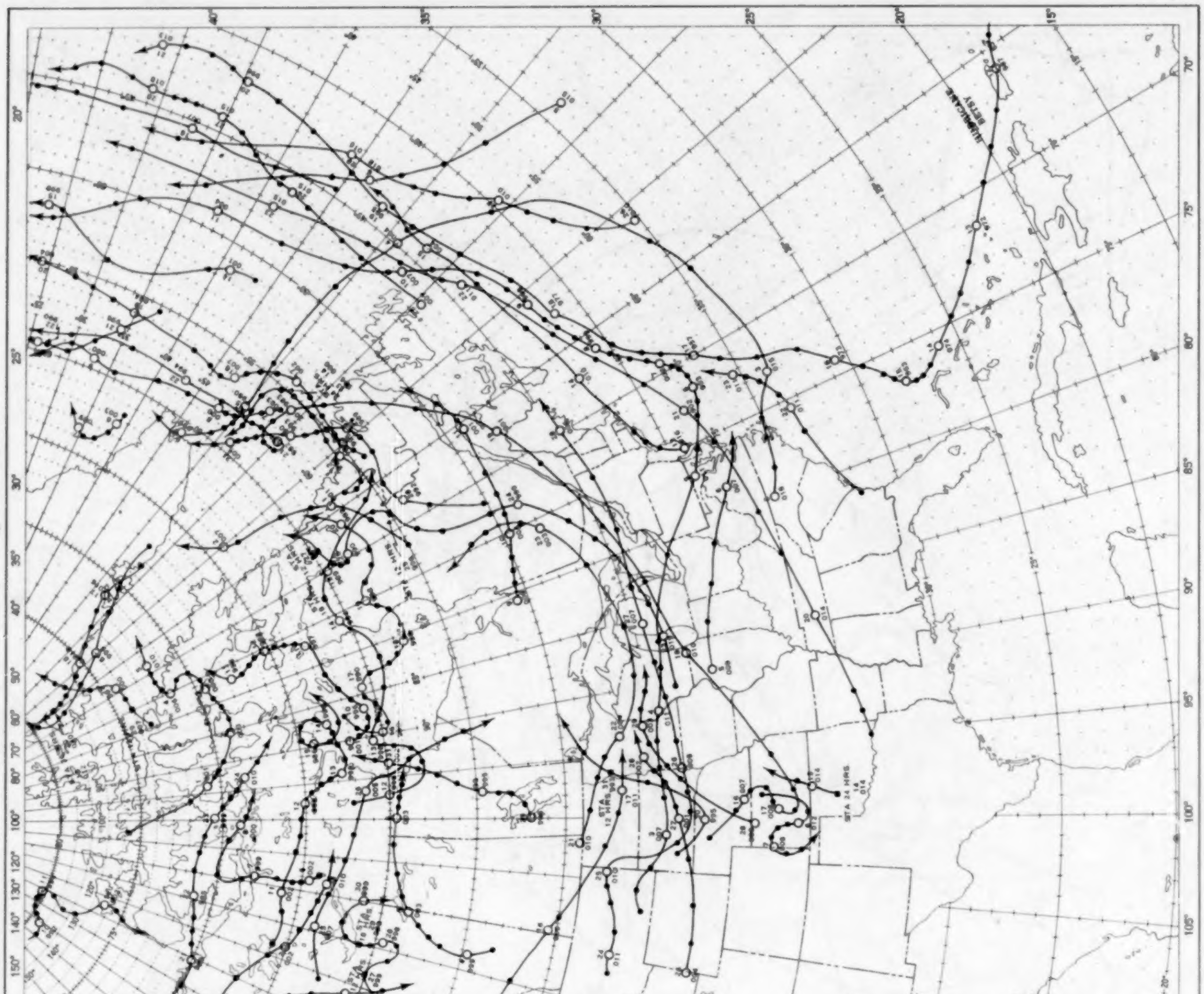

Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, August 1956.



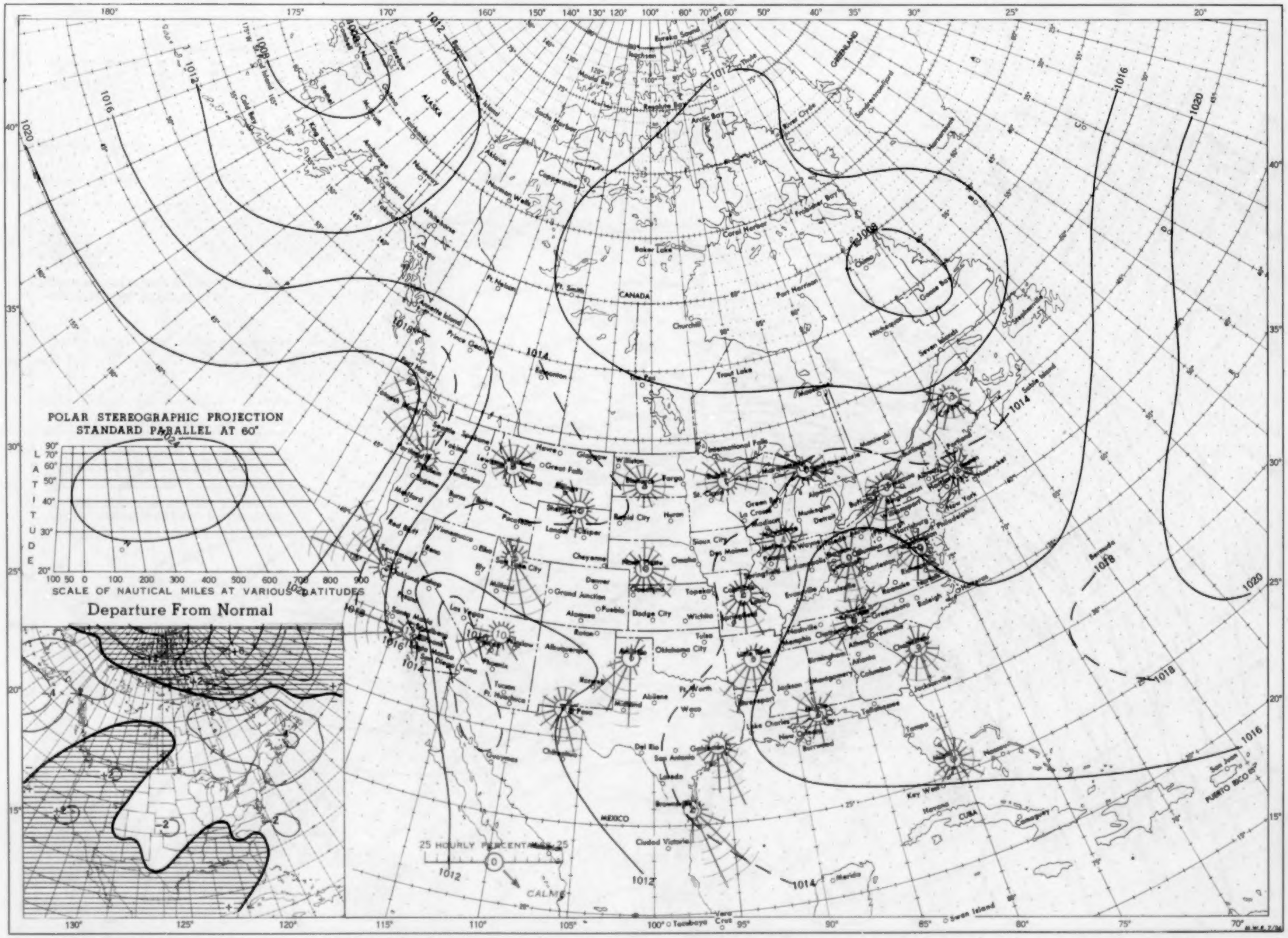

Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, August 1956.



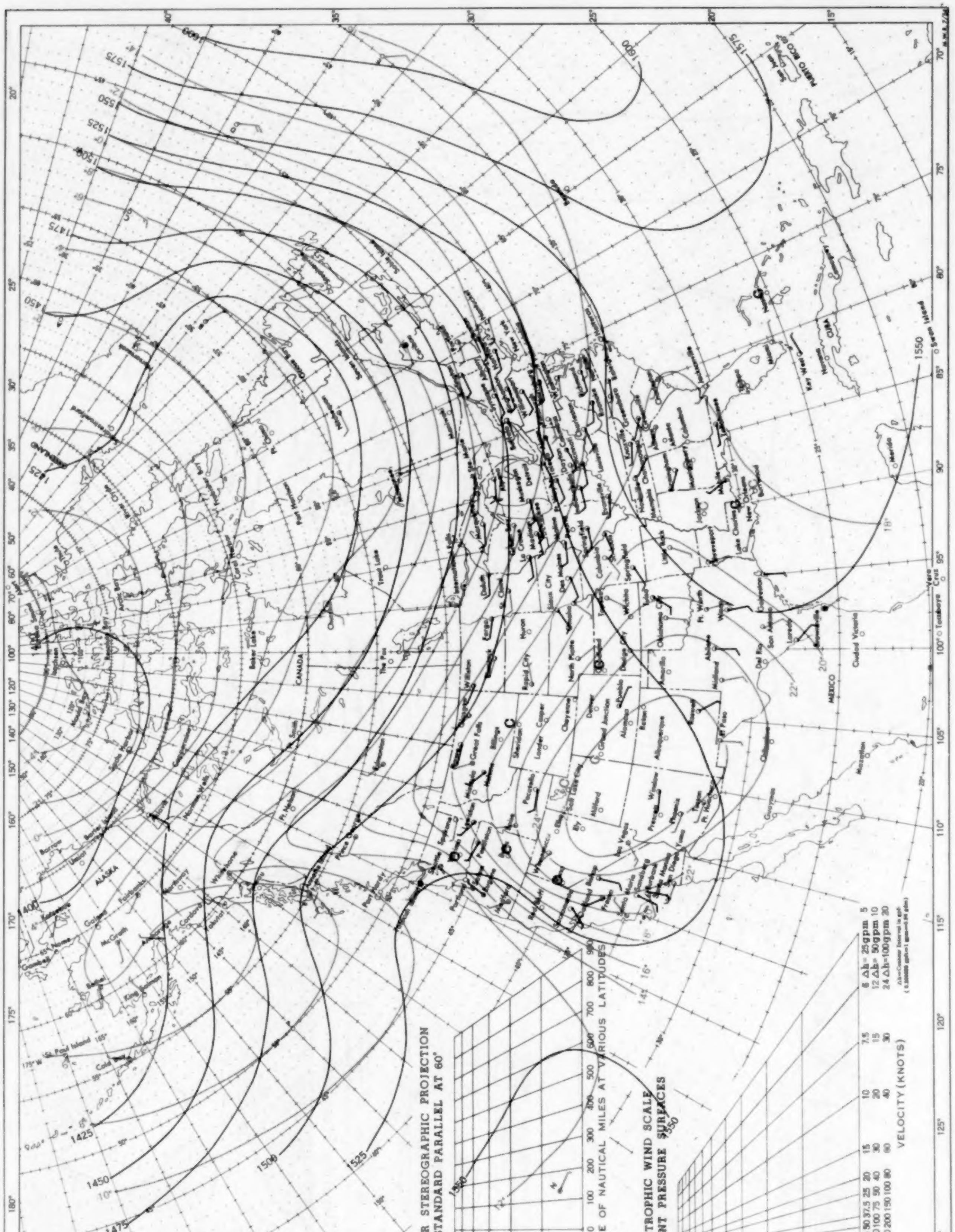

Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, August 1956. Inset: Departure of Average Pressure (mb.) from Normal, August 1956.



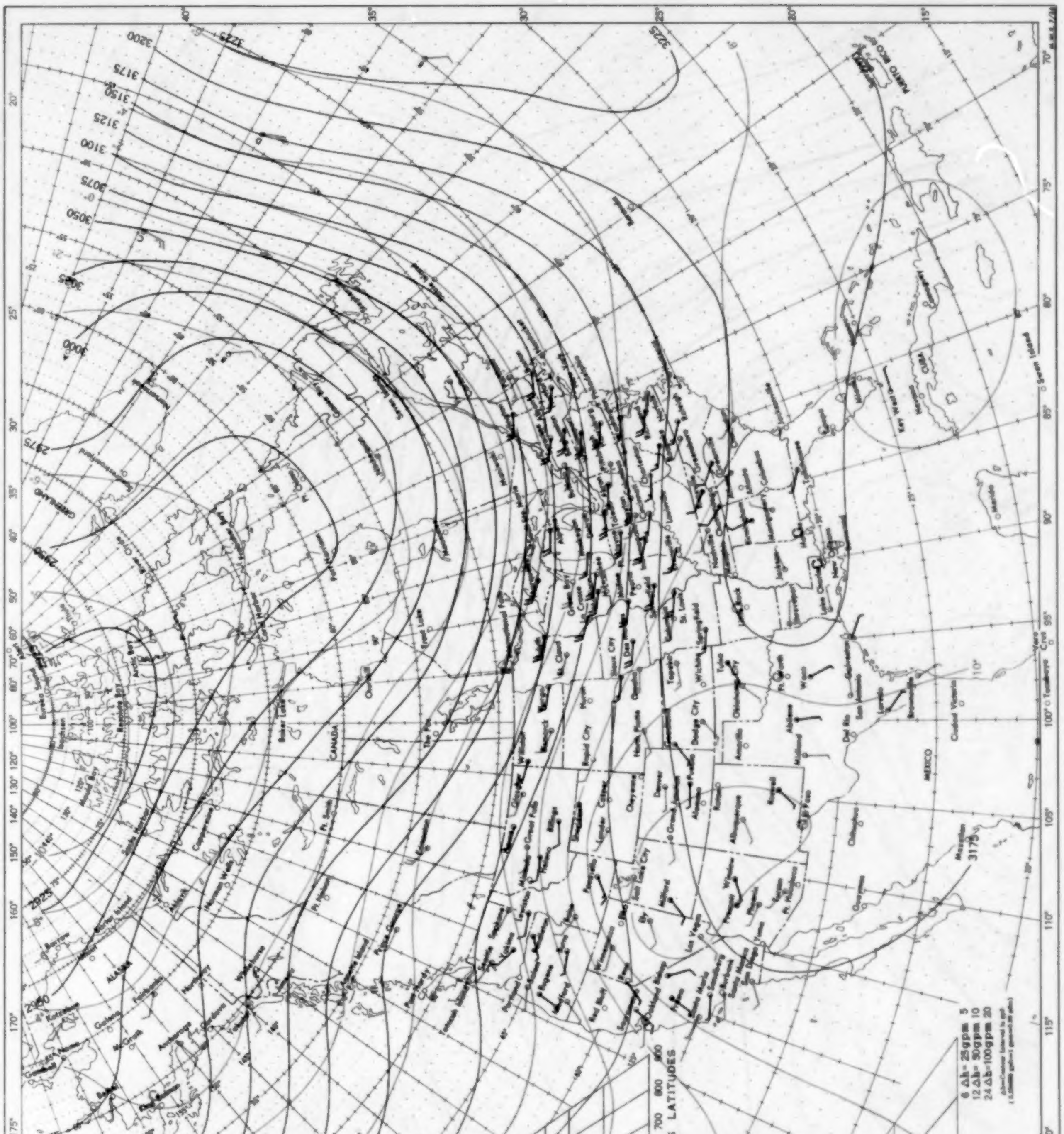

Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. 850-mb. Surface, 0300 GMT, August 1956. Average Height and Temperature, and Resultant Winds.



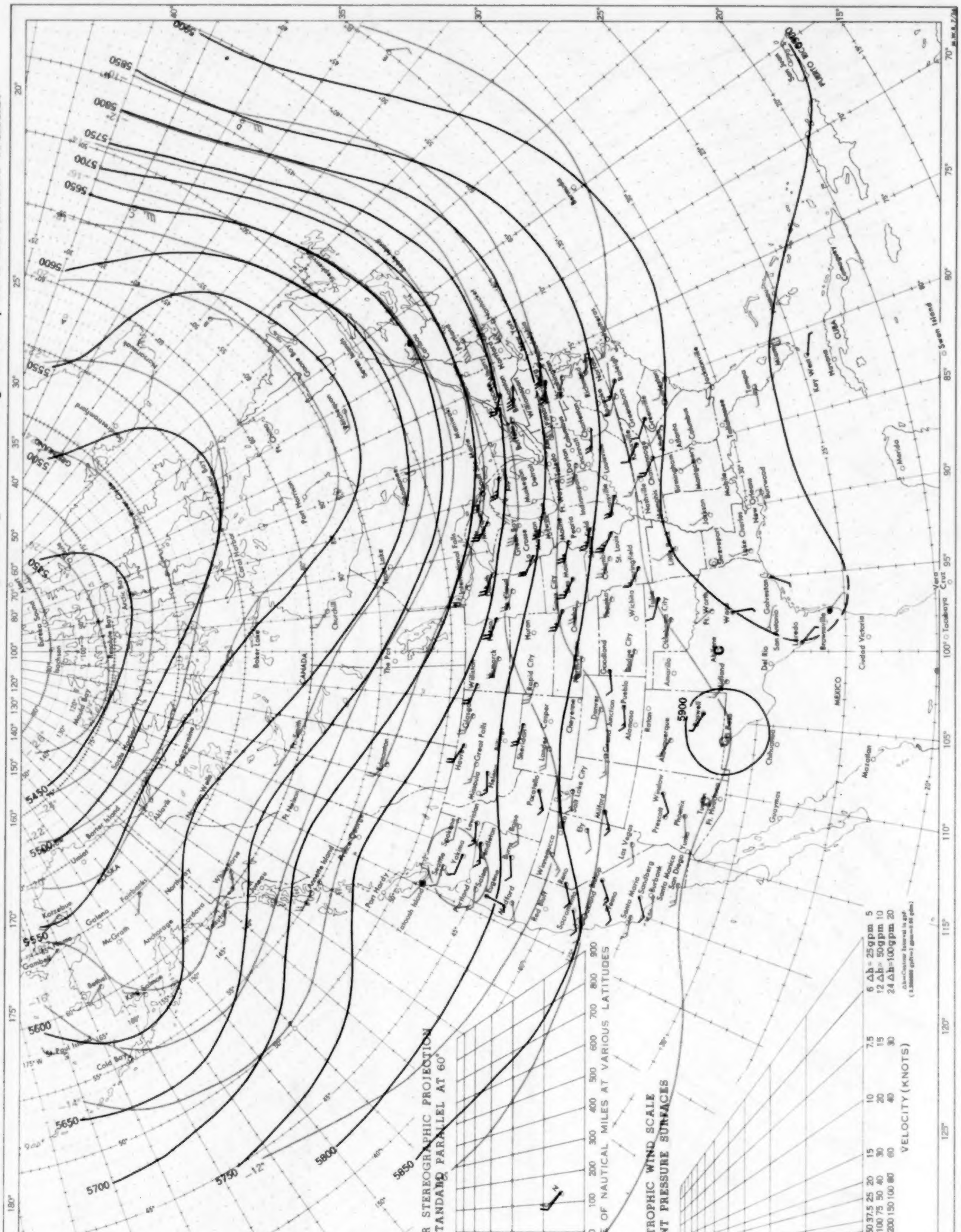

Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. Winds shown in red are based on rawins taken at the indicated pressure surface and time. Those in black are based on pibals taken at 2100 GMT and are for the nearest standard height level.

Chart XIII. 700-mb. Surface, 0300 GMT, August 1956. Average Height and Temperature, and Resultant Winds.



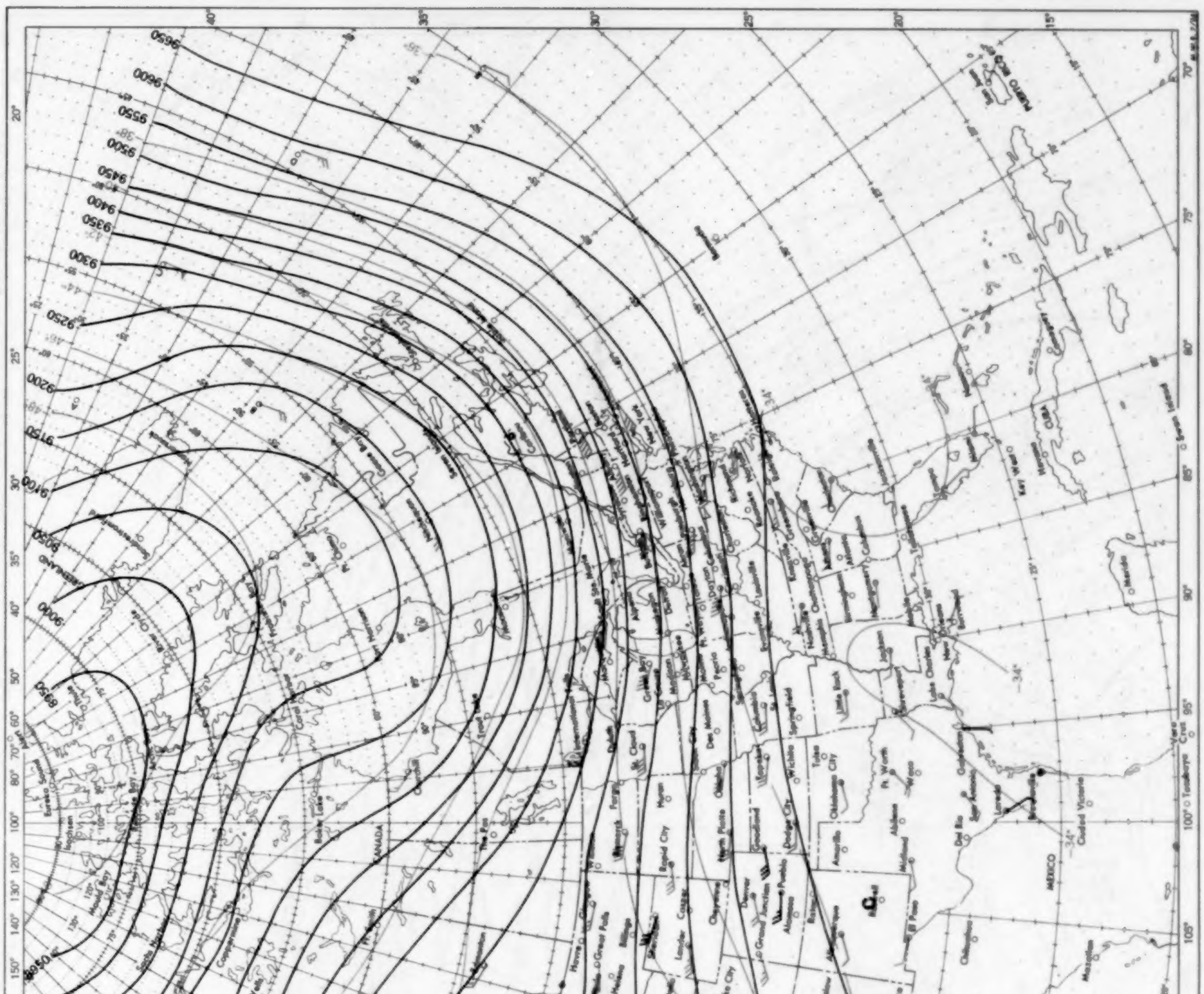

See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 0300 GMT, August 1956. Average Height and Temperature, and Resultant Winds.



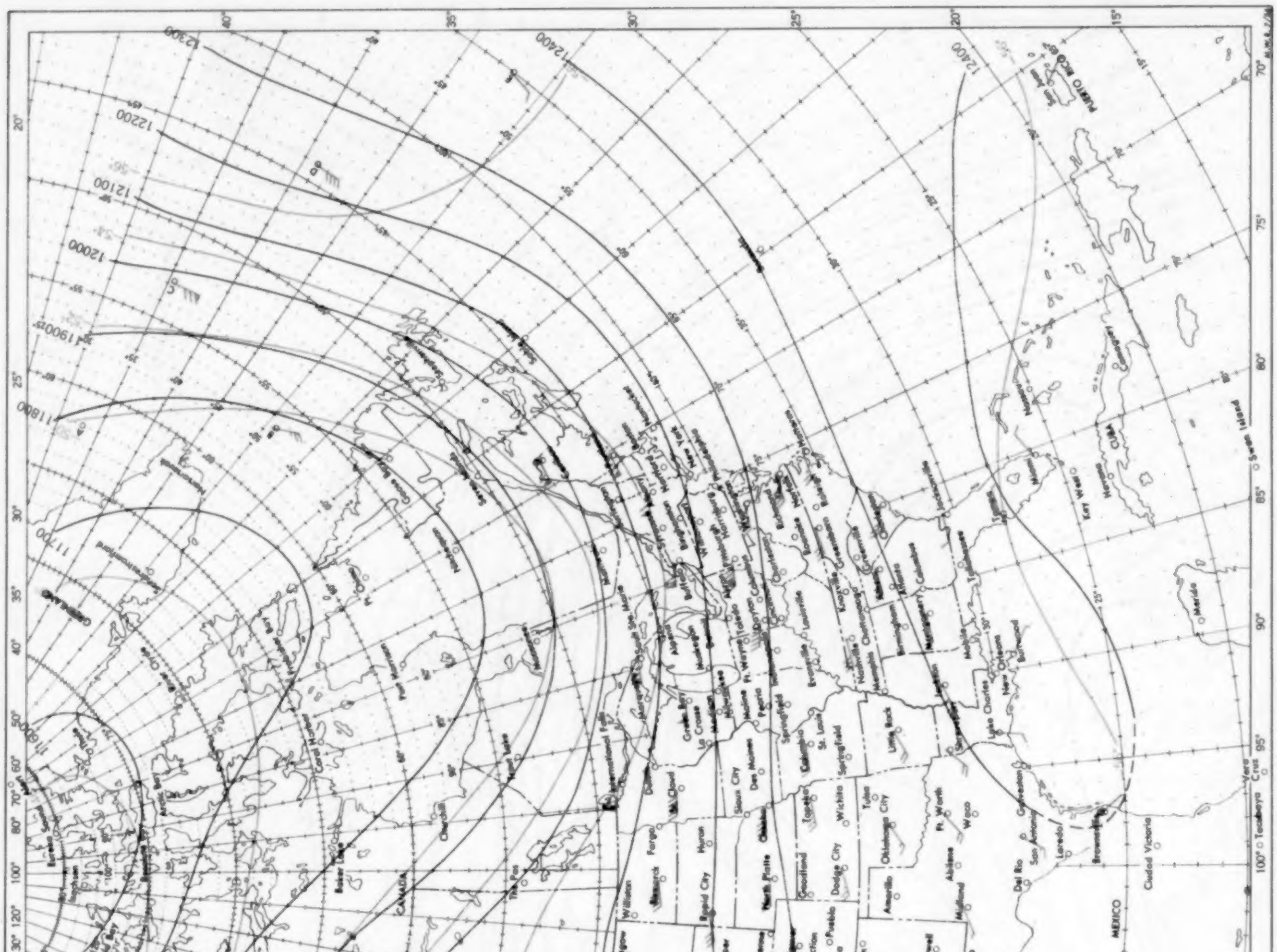

See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 0300 GMT, August 1956. Average Height and Temperature, and Resultant Winds.



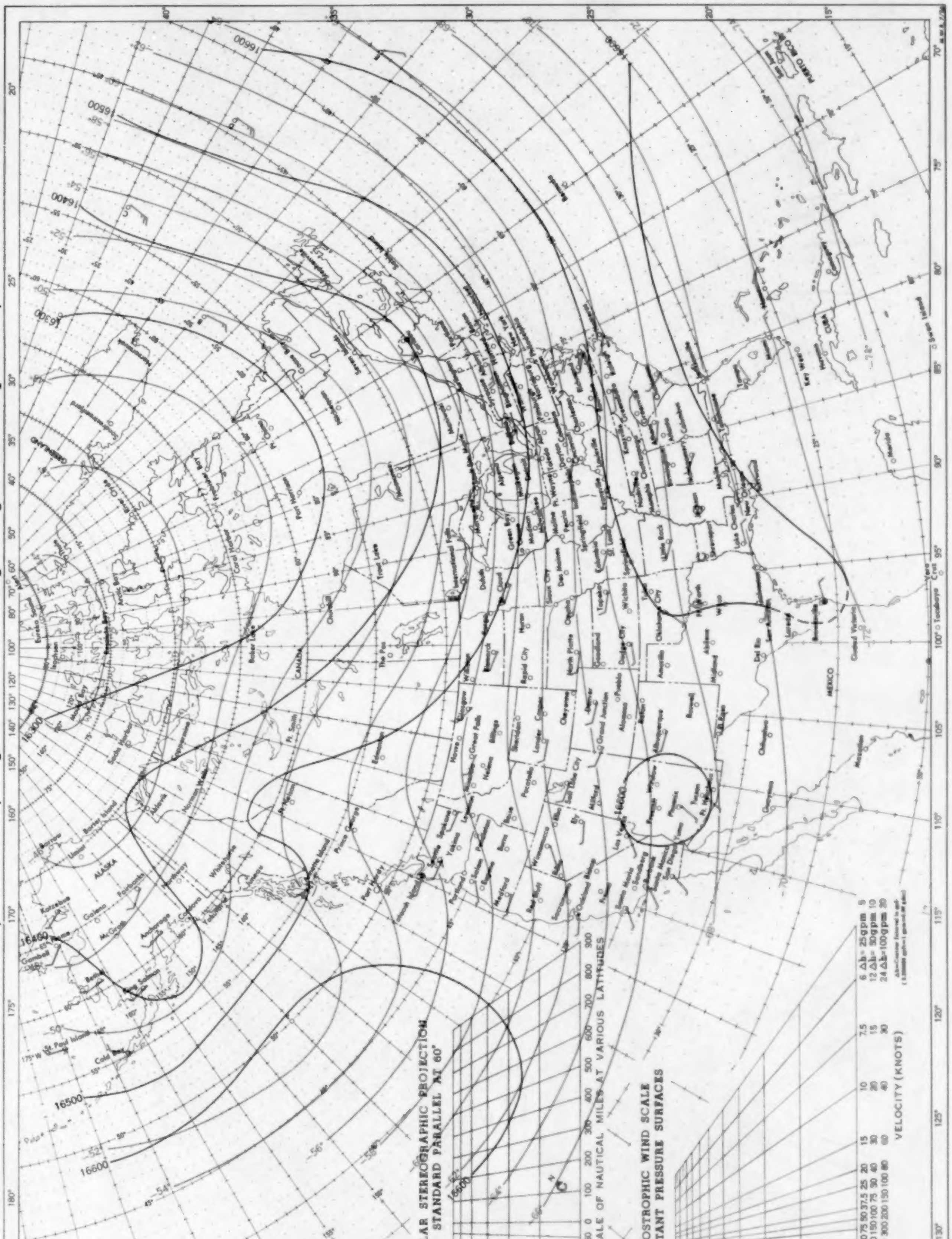

See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 0300 GMT, August 1956. Average Height and Temperature, and Resultant Winds.




See Chart XII for explanation of map. All winds are from rawin reports.

Chart XVII. 100-mb. Surface, 0300 GMT, August 1956. Average Height and Temperature, and Resultant Winds.




See Chart XII for explanation of map. All winds are from rawin reports.